



Atmospheres of the Giant Planets

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THE GIANT PLANETS — Jupiter, Saturn, Uranus, and Neptune — are fluid objects. They have no solid surfaces because the light elements constituting them do not condense at solar-system temperatures. Instead, their deep atmospheres grade downward until the distinction between gas and liquid becomes meaningless. The preceding chapter delved into the hot, dark interiors of the Jovian planets. This one focuses on their atmospheres, especially the observable layers from the base of the clouds to the edge of space. These veneers are only a few hundred kilometers thick, less than one percent of each planet's radius, but they exhibit an incredible variety of dynamic phenomena.

The mixtures of elements in these outer layers resemble a cooled-down piece of the Sun. Clouds precipitate out of this gaseous soup in a variety of colors. The cloud patterns are organized by winds, which are powered by heat derived from sunlight (as on Earth) and by internal heat left over from planetary formation. Thus the atmospheres of the Jovian planets are distinctly different both compositionally and dynamically from those of the terrestrial planets. Such differences make them fascinating objects for study, providing clues about the origin and evolution of the planets and the formation of the solar system.

Naturally, atmospheric scientists are interested to see how well the principles of our field apply beyond the Earth. For example, the Jovian planets are ringed by multiple cloud bands that move quickly, yet somehow remain fixed in latitude. On Earth such bands are disrupted by large transient storms at temperate latitudes and by long pressure waves that are anchored to the continents. Storms on the giant planets can endure for years or centuries, whereas on Earth they last for days or weeks.

Latitudinal banding is rather obvious on Jupiter and Saturn (*Figures 1,2*), which are heated by the Sun most strongly around their equators. On Uranus the heating patterns are dif-

Neptune and its Great Dark Spot, as recorded by Voyager 2 in 1989.

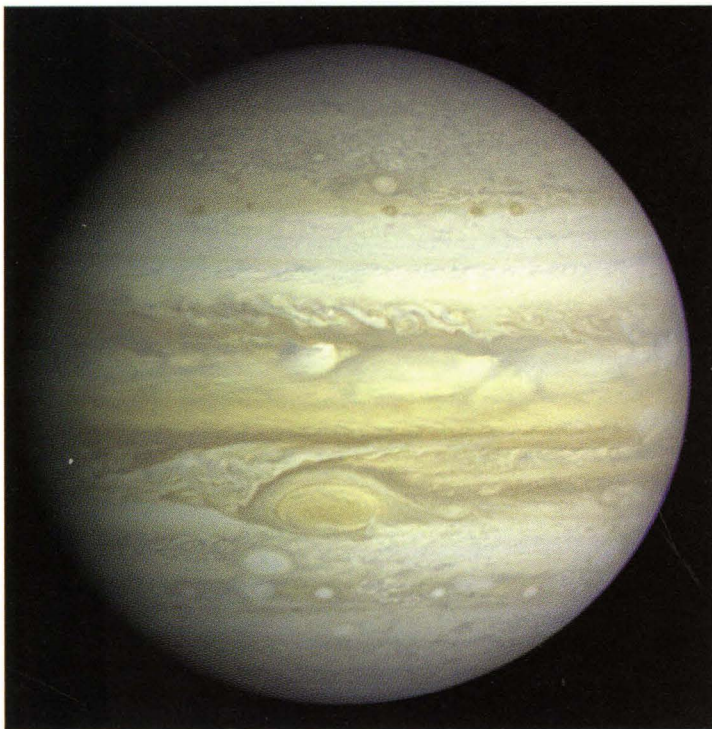


Figure 1. Strong east-west winds create a series of latitude-fixed bands on giant Jupiter, seen here as it appeared in February 1979 when imaged by Voyager 1 from a distance of 33 million km. The planet's Great Red Spot, below center, has intrigued astronomers for more than a century.

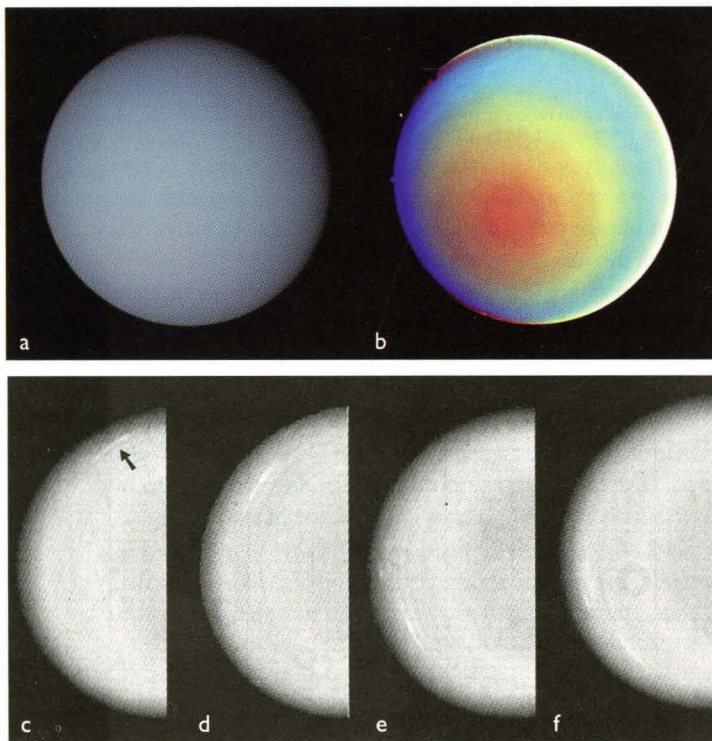


Figure 3. Voyager 2 views of Uranus. The color in *a* has been adjusted to simulate the view the eye would normally see. Features as small as 160 km would be visible — if Uranus had them. In *b*, computer processing has greatly exaggerated both the color and contrast; small doughnut-shaped features are artifacts caused by dust on the camera optics. In *c*, an arrow marks a convective plume at latitude -35° seen rotating around the disk. It is visible only because contrast has been greatly exaggerated.

ferent because the planet effectively spins on its side. During the Uranian year the Sun shines down on one pole then moves over the other, depositing more energy on average in the polar regions than at the equator. Nonetheless, latitudinal banding does exist, albeit weakly, making Uranus look like a tipped-over version of Jupiter and Saturn (*Figure 3*). Neptune also is banded (*Figure 4*). In fact, despite Neptune's great distance from the Sun and lower energy input, its winds are three times stronger than Jupiter's and nine times stronger than Earth's.

Chemistry provides another set of challenges for atmospheric scientists. On Earth, the composition of the air is determined largely by reactions with the solid crust, the oceans, and the biosphere. Even before the advent of life, photodissociation (the splitting of molecules by the ultraviolet component of sunlight) and the escape of hydrogen into space were causing our atmos-

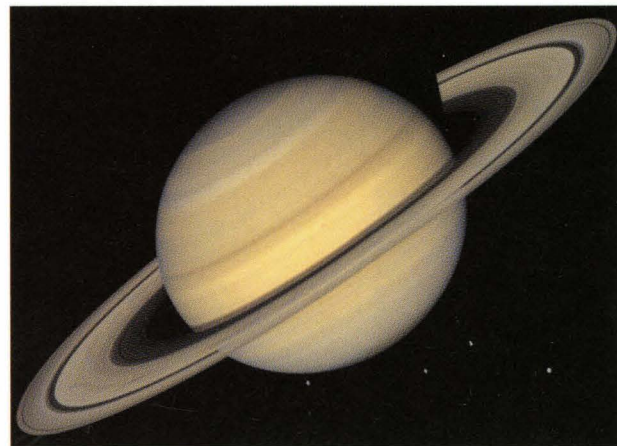


Figure 2. Voyager 2 recorded Saturn, its rings, and four major satellites from a distance of 21 million km in July 1981. Note that cloud bands on Saturn are fewer and lower in contrast than on Jupiter.

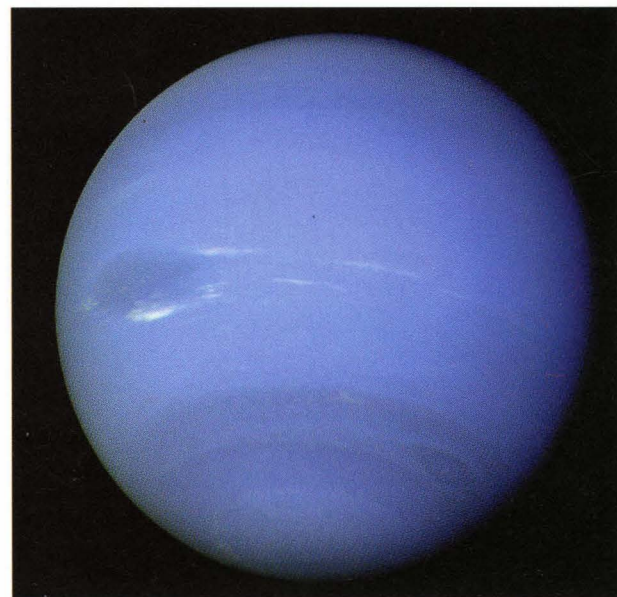


Figure 4. Neptune as seen by Voyager 2. The largest discrete feature, termed the Great Dark Spot, is accompanied along its southern edge by bright, high-altitude clouds of methane ice. As on Uranus, the blue color of Neptune is due in large part to the absorption of red light by methane gas.

phere to evolve. The Jovian planets have neither crust nor oceans nor life, and their gravitational fields are so strong that they retain all elements including hydrogen. Yet unstable compounds do form, by a variety of processes that include rapid ascent from the hot interior, photodissociation, condensation (cloud formation), electrical discharge (lightning; see *Figure 5*), and charged-particle bombardment (auroras; see *Figure 6*). As is evident from their multicolored clouds and abundant molecular species, the atmospheric chemistry of the Jovian planets is just as rich as Earth's.

With their internal heat and fluid interiors, the giant planets can be compared with the Sun and stars. On the other hand, we can relate their atmospheric phenomena to those on Earth. Our understanding of terrestrial atmospheric phenomena was inadequate to prepare us for the revelations made in recent years about the giant planets, but by testing our theories against these observations, we can understand the Earth in a broader context.

OBSERVATIONS

Our knowledge of the Jovian planets is derived from Earth-based telescopic observations begun more than 300 years ago, from modern observations from high-altitude aircraft and orbiting satellites, and from the wealth of data returned by interplanetary spacecraft. Pioneers 10 and 11 flew by Jupiter in the early 1970s, followed by Voyagers 1 and 2 in 1979; three of these eventually reached Saturn. Voyager 2 continued past Uranus in 1986 and Neptune in 1989. Comet Shoemaker-Levy 9 became an uninstrumented probe of Jupiter's atmosphere in 1994, preceding the arrival of the Galileo orbiter-probe spacecraft 17 months later.

Basic characteristics like mass, radius, density, and rotational flattening were determined during the first era of telescopic observation. Galileo's early views revealed the four large Jovian satellites that now bear his name. Newton estimated the mass and density of Jupiter from observations of those satellites' orbits. Others, using ever-improving optics, began to perceive atmospheric features on the planet. The most prominent of these, the Great Red Spot, can be traced back more than 150 years, and it may be older still.

Beginning in the late 19th century, astronomers made systematic measurements of Jovian and Saturnian winds by tracking features visually with small telescopes and, later, with photographs made through larger ones. Most recently, tens of thousands of features on Jupiter and Saturn have been tracked with great precision using the Voyager and Galileo imaging systems (*Figure 7*). The constancy of these currents over the centuries spanned by classical and modern observations is one of the truly remarkable aspects of Jovian and Saturnian meteorology. Uranus, on the other hand, is nearly featureless to the eye. Although the planet was discovered in 1781, the first definitive evidence for markings came from Voyager 2's images. Neptune is more photogenic than Uranus and exhibits faint markings that are visible from Earth with modern infrared detectors.

Astronomers began to decipher these planets' atmospheric compositions in the 1930s with the identification of absorptions by methane (CH_4) and ammonia (NH_3) in the spectra of sunlight reflected from their banded clouds. The detection of molecular hydrogen (H_2) followed around 1960. From these data,

observers verified that the proportions of hydrogen, carbon, and nitrogen in Jupiter's atmosphere were roughly consistent with a mixture of solar composition (see *Table 1*). Similar inferences have been made for Saturn, though observations of the compounds that contain these elements (like ammonia) are extremely difficult. The Galileo probe confirmed the spectroscopic estimate for C:H on Jupiter and detected several

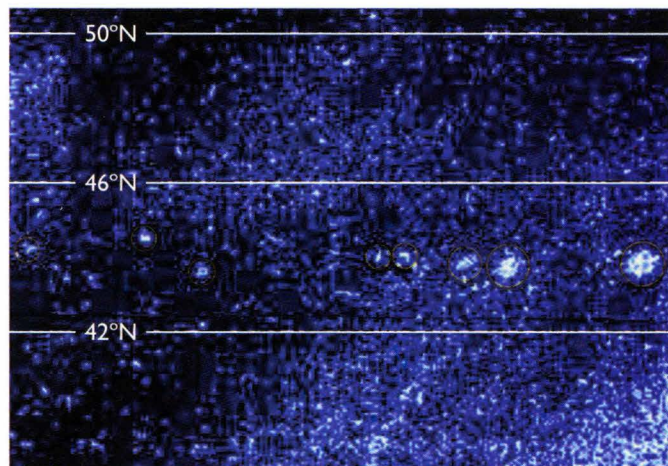


Figure 5. Enormous bursts of lightning (circled patches) were recorded on Jupiter's night side in November 1996 by the Galileo spacecraft. The view is 20,000 km wide. Clouds in the planet's atmosphere are faintly visible as well, illuminated by light from the moon Io. The individual flashes are hundreds of kilometers across and thus dwarf anything comparable on Earth. They lie just below a westward-moving jet at 46° north. Almost all the Jovian lightning seen by Voyagers 1 and 2 also occurred near the latitude of a westward-moving jet.

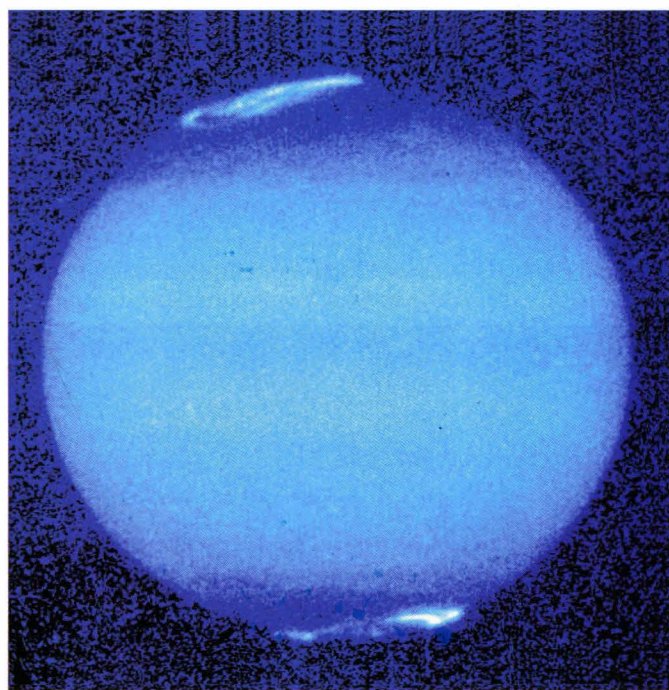


Figure 6. An ultraviolet image from the Hubble Space Telescope shows bright auroral rings encircling the north and south poles of Jupiter. They appear offset from the poles because Jupiter's magnetic field is offset from its spin axis by about 10°. The auroral emissions, which are situated about 500 km above the 1-bar pressure level, are caused by charged particles traveling toward the planet along field lines and striking the upper atmosphere.

Compositions of Outer-Planet Atmospheres

Molecule	Sun	Jupiter	Saturn	Uranus	Neptune
H ₂	84	86.4	97	83	79
He	16	13.6	3	15	18
H ₂ O	0.15	(0.1)	—	—	—
CH ₄	0.07	0.21	0.2	2	3
NH ₃	0.02	0.07	0.03	—	—
H ₂ S	0.003	0.008	—	—	—

Table 1. Percentage abundances (by number of molecules) for the giant planets' atmospheres below the clouds. Listed are six of the 11 most abundant elements in the Sun (and the universe). The others are the noble gases neon (Ne) and argon (Ar), and the metals silicon (Si), magnesium (Mg), and iron (Fe), all of which are believed to reside in these planets' cores. Here *Sun* refers to a mixture with the same proportion of elements as the primordial Sun, but cooled to planetary temperatures so that the elements combine to form the compounds listed. Values for Jupiter are from the Galileo probe; others are from remote sensing. All numbers are uncertain in the least significant figure and more so for Jupiter's water content. Dashes indicate unobserved compounds.

elements (sulfur, neon, argon) and isotopes (of carbon, helium, and hydrogen) for the first time.

We study the uppermost atmospheres of these worlds using three main techniques. First, when a spacecraft appears to pass behind a planet (an occultation), electrons in the planet's ionosphere affect the craft's radio signal en route to Earth; the change of electron density with altitude is a measure of temperature. Second, the ultraviolet spectrum of sunlight and starlight that has passed through the upper atmospheres contains information about temperature and composition. And third, by observing excitation processes like auroras (*Figure 6*) and airglows, we learn about the energy sources for high-altitude chemical reactions; these can alter the composition of deeper layers if stable compounds are formed and convected downward.

The temperatures and energy budgets of the giant planets have been studied from Earth for decades, but the best determinations have come from spacecraft. Their infrared and radio-occultation experiments probed from the stratosphere (where

temperature increases with height) down into the troposphere (where the clouds are; *Figure 8*). By comparing the infrared emission with the energy absorbed from sunlight, we can measure the planets' energy budgets and determine the strength of their internal heat sources.

GLOBAL PROPERTIES

The solar composition model does not exactly fit the composition of any planetary atmosphere, but it is a useful standard. The C:H ratio for Jupiter is 2.9 times solar. For Saturn it is more than three times solar, and for Uranus and Neptune the ratios are 30 to 40 times solar. This enrichment of heavy elements relative to hydrogen probably occurred when light gases like hydrogen and helium were blown out of the solar system by the active young Sun. Jupiter and Saturn formed early enough to protect most of their light gases. Uranus and Neptune formed more slowly, presumably because the primordial solar nebula was less dense at its outer edge and took longer there to pull itself together into planet-sized objects (see Chapter 2).

Helium, the second most abundant element in the Sun, has no detectable spectral signature to make its presence known. However, collisions between helium and hydrogen molecules alter the latter's ability to absorb infrared light, an effect that the Pioneer and Voyager instruments could detect and thus give us a kind of "back-door" identification of helium. And we can also combine infrared measurements with the radio-occultation data obtained as the spacecraft passed behind the planets to determine the molecular weight of the atmospheric mixtures. When paired together, these two methods yield helium abundances with an uncertainty of only a few percent. The Galileo probe's result for Jupiter is accurate to better than 1 percent.

The helium abundances tell an interesting story. The values for Uranus and Neptune, 15 and 18 percent by volume, respectively, are consistent with a gas mixture of solar composition, about 16 percent. However, the values derived for Saturn (3 percent) and Jupiter (13.6 percent) suggest that helium has

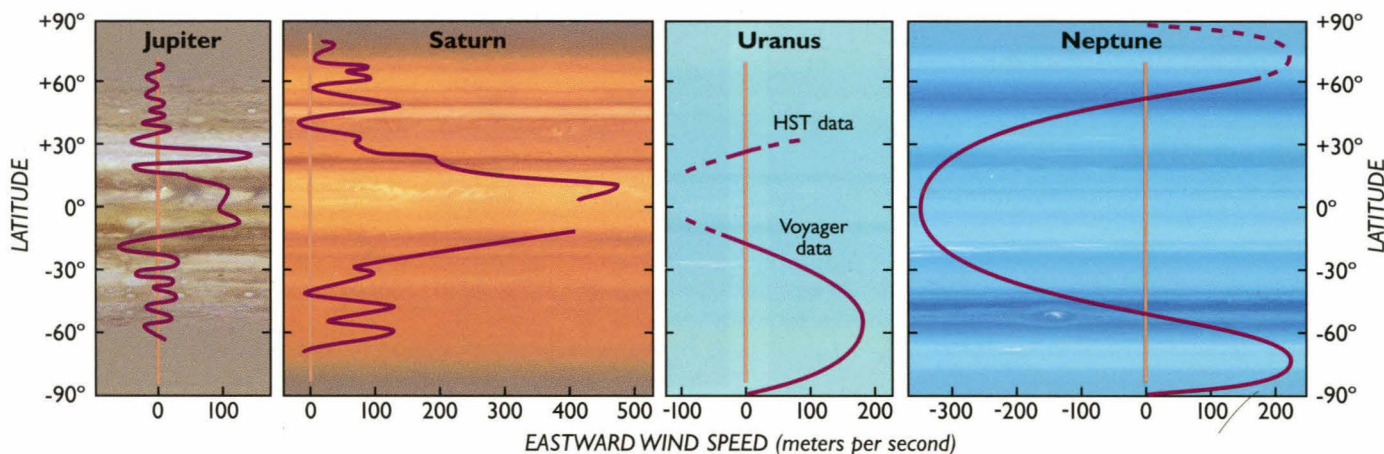
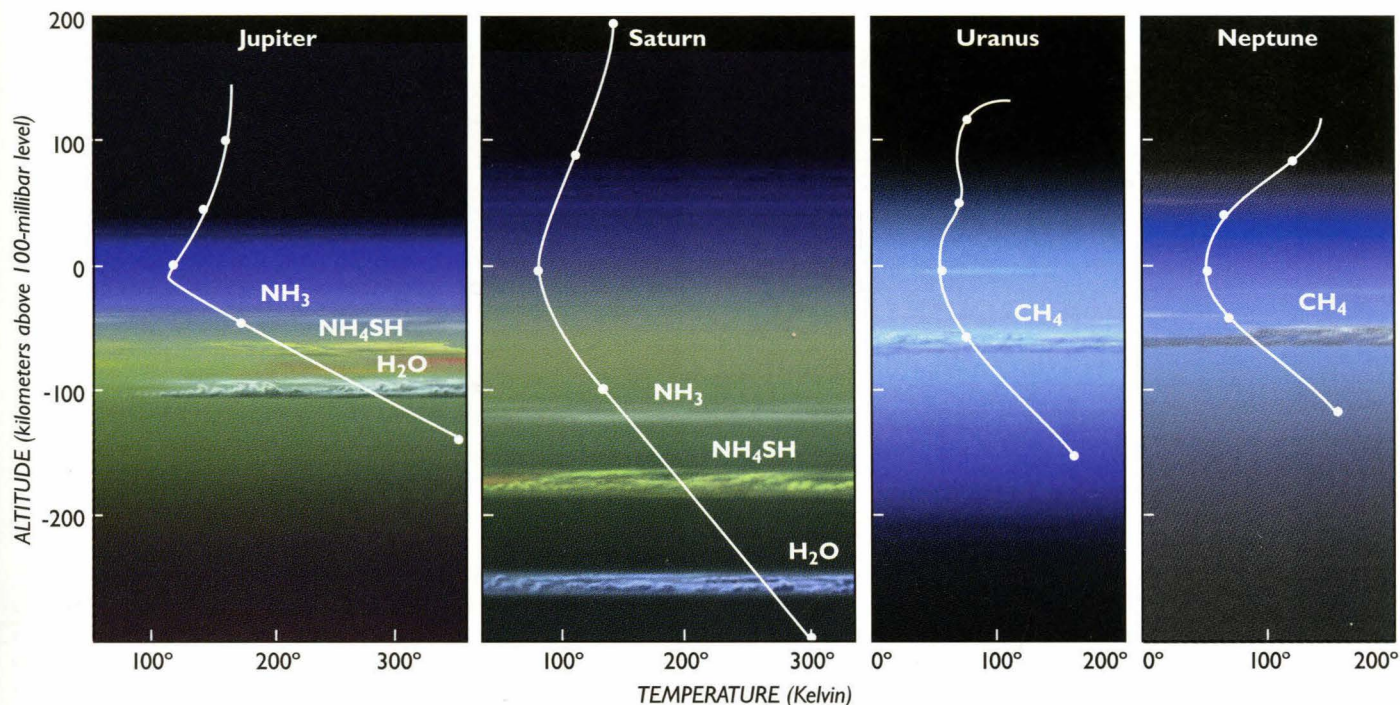


Figure 7. Winds on the giant planets vary in speed and direction with latitude. Positive velocities correspond to winds blowing in the same direction but faster than the planets' internal rotation periods, which are based on observations of their magnetic fields and periodic radio

emissions. Negative velocities therefore, are winds moving more slowly than these reference frames. The equatorial jets are slower than the planets' rotation on Uranus and Neptune, faster on Jupiter and Saturn. In fact, the winds are faster on Saturn than on any other planet.



been depleted from Saturn's upper atmosphere and probably Jupiter's as well. This depletion is consistent with theories of the planets' internal histories: at sufficiently low temperatures, helium raindrops form in the metallic hydrogen interiors and settle toward the core. On Uranus and Neptune, pressures are not high enough to form metallic hydrogen, so no depletion occurs. And the interior of Jupiter has not cooled down as much as Saturn's, so its depletion has not been as great.

The giant planets radiate to space from a range of altitudes centered in the 0.3- to 0.5-bar pressure range. The temperatures there are 124° K for Jupiter, 95° K for Saturn, and 59° K for both Uranus and Neptune (*Figures 8,9*). Sunlight is absorbed over a broader range, down to pressures of 5 bars or more. The brightness at visible wavelengths determines the planet's *albedo*, which is the fraction of incident sunlight reflected to space. The remaining fraction is absorbed and goes into heating the atmosphere.

From these observations, we infer that Jupiter and Saturn radiate about 1.7 and 1.8 times more heat, respectively, than they absorb from the Sun. Such "infrared excesses" are an indication that each planet is releasing internal heat that remains from planetary formation. Uranus and Neptune emit at the same temperature even though Neptune is 1.6 times farther from the Sun. This implies that Uranus has at most a small internal heat source (its estimated ratio of emitted to absorbed heat is below 1.1), but that Neptune has a relatively large one (its ratio is near 2.6). Such infrared excesses, or lack thereof, provide us with additional insight into internal structures and histories, as explained in Chapter 14.

The ways that temperature and infrared emissions vary with latitude on the giant planets (*Figure 9*) indicate how effective the winds are in redistributing heat away from the subsolar zone. As a reminder, the Sun heats the equators of Jupiter, Saturn, and Neptune more than their poles, while on Uranus the situation is reversed. But in all four cases the temperature dif-

Figure 8. Pressure-temperature profiles for the upper atmospheres of the giant planets, as determined by Voyager measurements at radio and infrared wavelengths. Altitudes are relative to the 100-mb pressure level, and the dots are spaced to indicate tenfold changes in pressure. For Jupiter and Saturn the altitudes of predicted cloud layers are based on a gaseous mixture of solar composition. For Uranus and Neptune, solar composition grossly underestimates the amounts of condensable gases, and only the methane cloud detected by Voyager 2 is shown. Temperatures are generally lower on planets farther from the Sun, except for Neptune, whose internal heat source makes it as warm as Uranus. The range of cloud altitudes is narrower on Jupiter because gravity is stronger there and compresses the atmosphere more than on the other planets

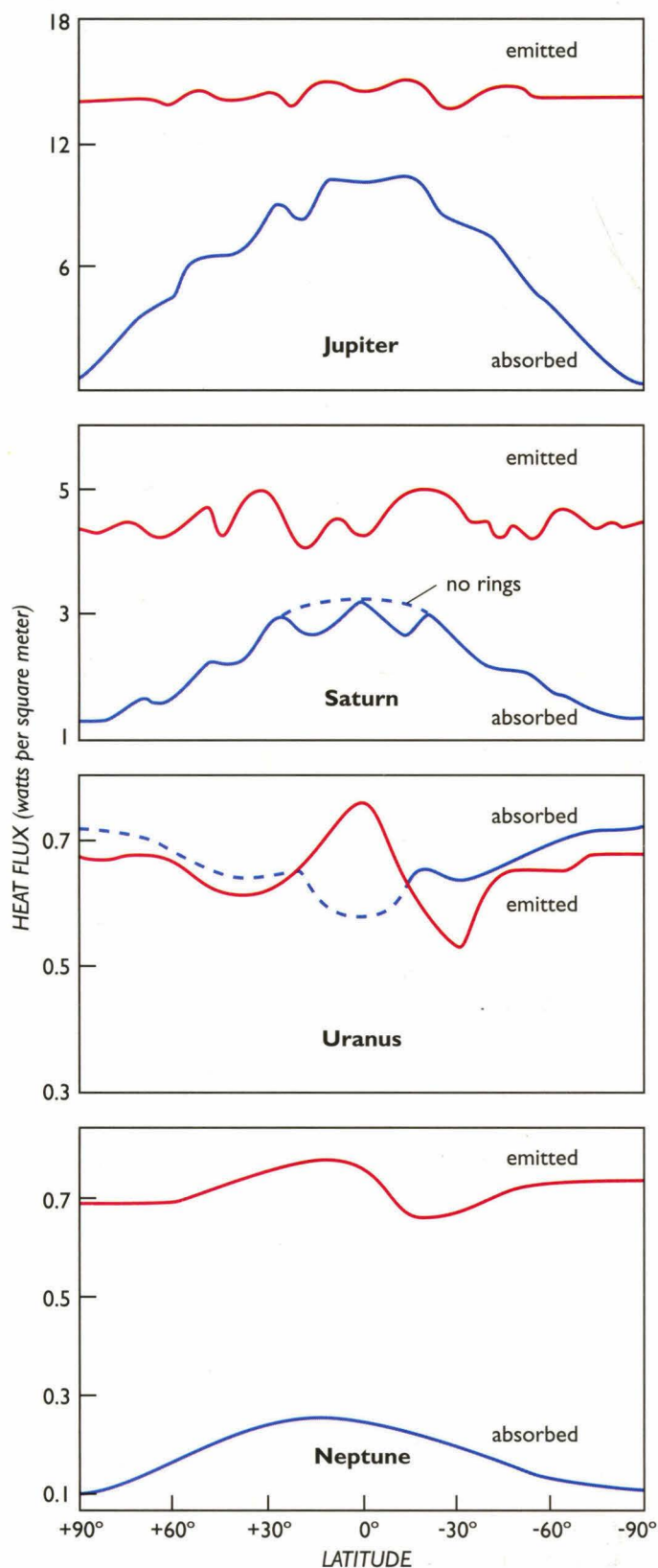
ferences with latitude are small, less than what they would be without winds. Even so, this does not automatically mean that the energy redistribution is taking place within the cloud layers — an interesting question (dealt with more fully later) is whether the redistribution of heat takes place instead in the planets' fluid interiors.

CLOUDS AND VERTICAL STRUCTURE

Temperatures, pressures, gas abundances, cloud compositions — all as functions of altitude and horizontal position — are the principal components of atmospheric structure. Atmospheric dynamics, discussed in the next section, concerns the causes and effects of wind. However, the distinction between structure and dynamics is not always clear. Circulation alters the structure by carrying heat, mass, and chemical species from place to place. The structure, in turn, controls the absorption of sunlight, its re-emission as infrared radiation, and the release of latent heat during condensation — all of which cause the gas to heat up, expand, and set winds in motion.

Atmospheres are self-supporting in that the increase of pressure with depth provides the upward force needed to balance the downward pull of gravity. This balanced state is known as

hydrostatic equilibrium. The degree of compression of the gas is proportional to the gravitational acceleration present and inversely proportional to its temperature. Thus the outer atmospheres of Jupiter and Neptune are the most compressed and also the thinnest — that is, the altitude range over which pressure increases tenfold is less than on Saturn and Uranus.



The variation of temperature with depth is controlled by different processes at different altitudes (*Figure 8*). At pressures greater than about 1 bar, rapid convective motions have what is termed an *adiabatic gradient* of temperature. That is, temperature decreases with altitude at the same rate as it would in a rapidly rising parcel of air. The parcel expands and does work at the expense of its own internal energy (and hence temperature). Mixing creates a state where all air parcels resemble one another, and the resulting temperature change with height is then considered adiabatic.

Deep down, heat is effectively trapped in the atmosphere's gases. To move upward, heat must be carried by convection until it reaches a level where the overlying atmosphere is no longer opaque to infrared radiation. For the giant planets, this transition occurs at pressures of 100 to 300 mb, at which point the atmosphere can radiate its heat directly to space. Infrared cooling creates a temperature minimum in this altitude range. Above the 100-mb level, the temperature increases with height because the atmosphere there is absorbing sunlight. Atmospheric gases alone probably cannot absorb energy efficiently enough to account for the rise in temperature. But a haze layer, produced photochemically in the stratosphere, could absorb the extra sunlight required to heat its surroundings.

Higher up, in what is termed the thermosphere, the gas is so thin that even small energy inputs can change its temperature significantly. For instance, the aurora is caused by electrically charged particles striking the upper atmosphere. The particles follow the magnetic field lines that originate far downstream in the wake of the planet in the solar wind flow. The auroral zone is the high-latitude oval where these field lines intersect the atmosphere (*Figure 6*). Spread over the planet, the energy of the incoming charged particles causing the auroras is equivalent to only 0.001 percent of the total incident sunlight, but that is a large input at these altitudes. Solar photons alone would produce temperatures only near 200° K. The cascade of charged particles seems capable of heating the Jovian thermosphere to 1,000° K. The dissipation of electrical currents and upward-propagating waves might also be contributing to the high temperatures, but there are large uncertainties associated with all of these energy sources. The thermosphere sheds its heat principally by conducting it downward to the cooler layers below.

Once the pressure-temperature curve for an atmosphere has been determined, the vertical cloud structure can be inferred.

Figure 9. A comparison of absorbed solar energy and emitted infrared radiation, averaged with respect to longitude, season, and time of day. Jupiter, Saturn, and Neptune each radiate away more energy than they absorb, implying an internal heat source. This radiation is also distributed more uniformly than the absorbed sunlight, which suggests heat transport across latitude circles at some depth within the planet. The dashed curve for Saturn shows how much sunlight it would absorb without the shadowing caused by its ring system. The dashed curve for Uranus is an extrapolation northward of Voyager's measurements, which assumes that planet's absorption of heat is symmetric with respect to latitude over the course of a Uranian year. Small bumps are due to temperature and brightness differences between adjacent latitude bands.

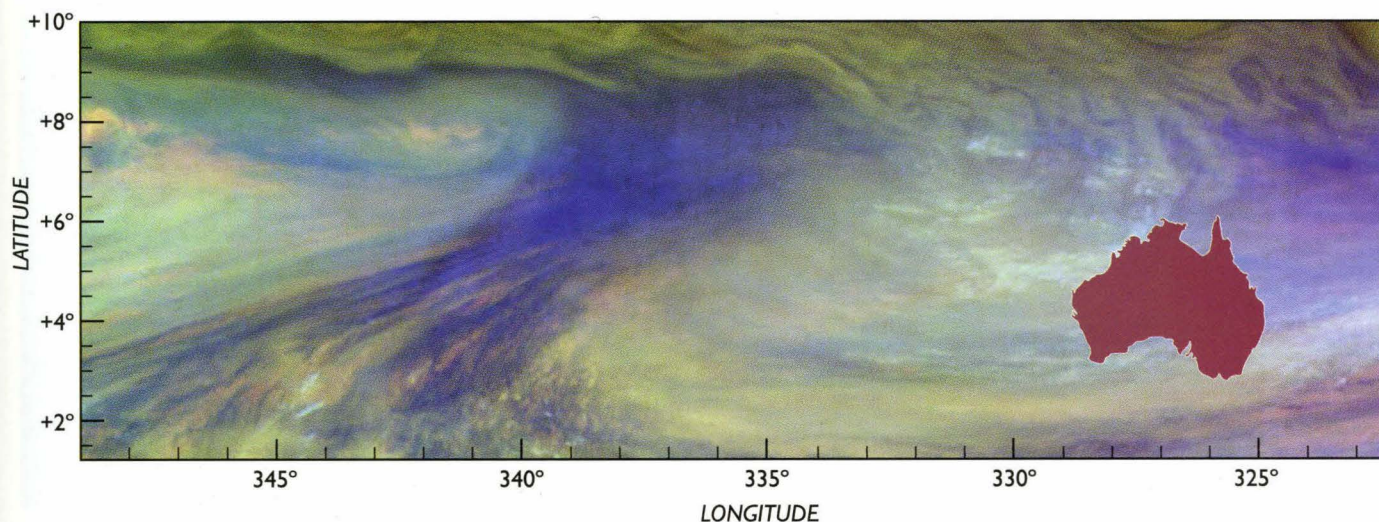
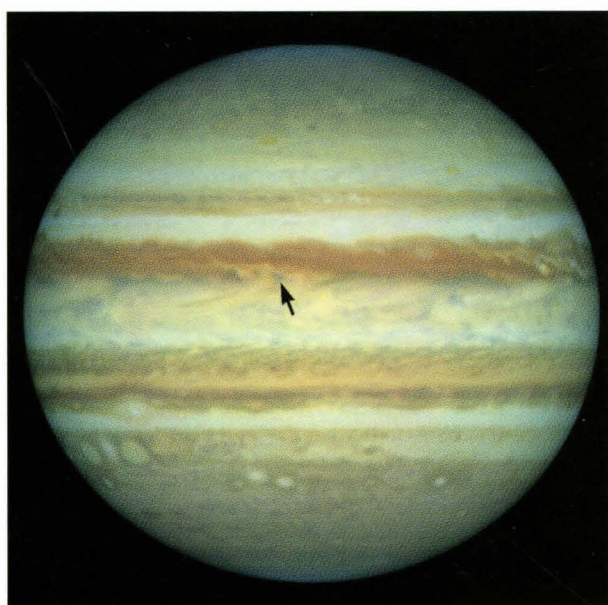
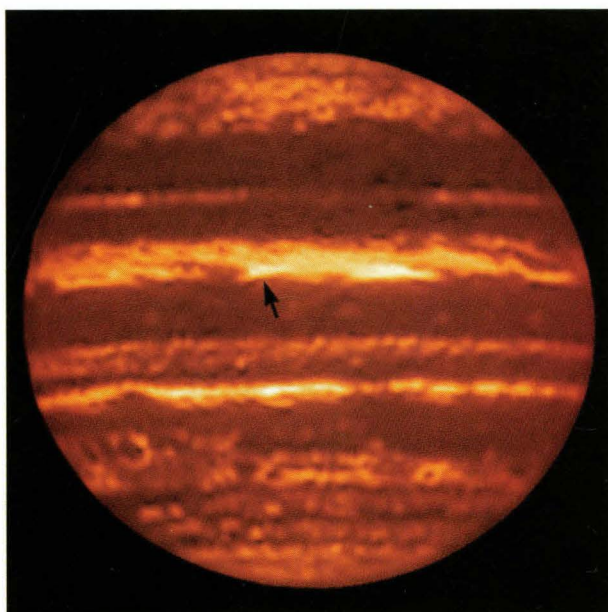


Figure 10 (above). An equatorial hotspot on Jupiter, as seen by the Galileo spacecraft. This mosaic combines three near-infrared images to show variations in altitude: bluish clouds are high and thin, reddish ones are low, and white clouds are high and thick. Dark blue marks a hole in the deep cloud with an overlying thin haze. The silhouette of Australia is shown to scale.

Figure 11 (right). These infrared (top) and visible-light (bottom) views of Jupiter were obtained, respectively, by the Infrared Telescope Facility on 3 October 1995 and by the Hubble Space Telescope one day later. Holes or thinnings in the upper cloud deck allow radiation to escape to space from warmer layers underneath, creating *hotspots* that appear bright at wavelengths near 5 microns in the infrared. The views match in longitude within 2°, and arrows mark where the Galileo probe entered the atmosphere on 7 December 1995.



One first computes the altitudes at which the different atmospheric constituents can condense by assuming that the gas mixture has a uniform, known composition, like those in Table 1. A particular gas will condense when its absolute abundance (partial pressure) exceeds its abundance at its dew point (the saturation vapor pressure). Since the latter falls rapidly as the gas cools, clouds will form at the coldest layers in the atmosphere. These condensates will collect into drops and rain out in the absence of buoyant updrafts, so they should be found above the cloud-forming levels only as high as upward convection will carry them.

These calculations argue for three distinct cloud layers on Jupiter and Saturn (Figure 8). The lowest is composed of water ice or possibly water droplets. Next are crystals of ammonium hydrosulfide (NH_4SH), which is basically a combination of ammonia (NH_3) and hydrogen sulfide (H_2S). At the top we expect an ammonia-ice cloud. These three layers are also present in the colder atmospheres of Uranus and Neptune, but they should lie deeper down — at higher pressures — because the low temperatures necessary for cloud formation exist at greater depths. Even methane will condense if the temperature gets low enough, especially if the gas is abundant. Apparently, such conditions are met on Uranus and Neptune, where a layer of condensed methane overlies the other clouds. Voyager 2's radio signal probed down to the 2-bar level and detected the methane cloud at 1.3 bars but not the ammonia cloud.

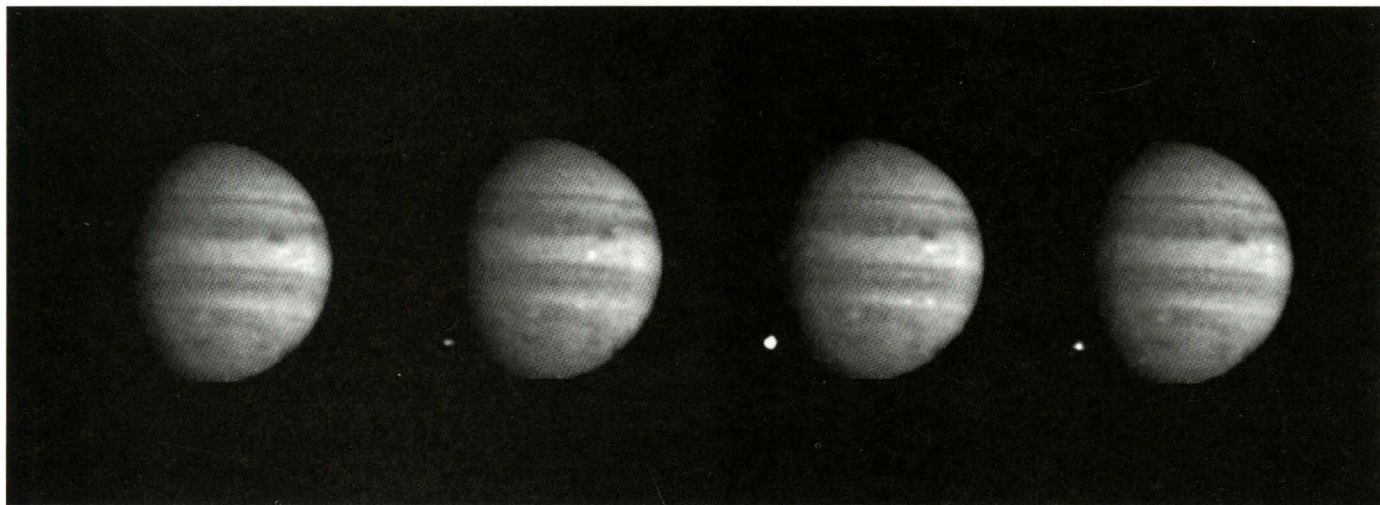


Figure 12. When fragment W from Comet Shoemaker-Levy 9 struck Jupiter on 22 July 1994, the Galileo spacecraft recorded these green-filtered images every 2.3 seconds, beginning at left. The comet's numerous fragments hit on the dark side of Jupiter near the dawn terminator. At its peak the light from fragment W's annihilation was 1.5 percent of Jupiter's brightness at this wavelength.



Figure 13. The impact site from fragment G of Comet Shoemaker-Levy 9, recorded 1.7 hours after G's entry into Jupiter's atmosphere on 18 July 1994. The aftermath was captured by the Hubble Space Telescope after Jupiter's rotation had carried the site into daylight. Dark material, covering an area comparable to Earth, was emplaced within 15 minutes of the impact. The thin ring has been interpreted as either a propagating wave or an outward-spreading flow of debris. The small dark spot to its left marks where fragment D struck some 20 hours (two rotations) earlier.

The layered-cloud model may be too simple, however. Below the water-cloud base, which for Jupiter is at the 5-bar level, the atmosphere should be well-mixed by convection and its composition constant, matching that of the planet as a whole. Yet the Galileo probe found a rather different situation. While the abundances of NH_3 , H_2S , and H_2O it measured were well below solar values at 5 bars, NH_3 and H_2S reached three times solar at the 10-bar level and water's abundance was still increasing when the probe's signal failed near a depth corresponding to 20 bars. Part of this inconsistency is that the probe apparently descended into a "hotspot," a region of intense infrared emission made possible by a gap in the clouds (*Figures 10,11*). Perhaps these hotspots are the deserts of Jupiter, where dry air from high altitudes is forced downward, as occurs over the Earth's subtropical regions. In that case, the weather forecast for a Jovian hotspot is always "sunny and dry."

Jupiter is not dry everywhere — the hotspots are relatively rare (*Figure 10*), and the Galileo orbiter has found atmospheric pockets elsewhere with water abundances 100 times greater than that in the hotspots. Also, since hydrogen and oxygen are the first and third most abundant elements in the Sun (with helium the second), water should be the most abundant compound on the giant planets — assuming everything formed from the same cloud of gas and dust as the Sun. Still, water has been an extremely elusive molecule on the giant planet. Spectroscopic observations from Earth reveal only small amounts of water vapor, because most of it freezes at the cold Jovian cloud tops.

Similar arguments apply to H_2S , which remained undetected from Earth until fragments of Comet Shoemaker-Levy 9 slammed into Jupiter and dredged up material from below the clouds (*Figures 12,13*). These unprecedented data are difficult to interpret because we don't know how much of the material came from the comet and how much from Jupiter's atmosphere. Nevertheless the detected compounds included CO, NH_3 , S_2 , and various metals, but not SO or SO_2 . The implication is that the sulfur (as H_2S) and oxygen (as H_2O) are physically separated in Jupiter's atmosphere.

If the giant planets' atmospheres were in chemical equilibrium, with hydrogen the dominant species, virtually all their carbon would be tied up in methane, all the nitrogen in ammonia,

all the oxygen in water, and so on. But in Jupiter's case, we have identified ethane (C_2H_6), acetylene (C_2H_2), carbon monoxide (CO), and other gases that imply disequilibrium. Both C_2H_6 and C_2H_2 are relatively easy to account for, since they form in the upper atmosphere as recombined byproducts of methane photodissociation. These gases are seen on Saturn and Uranus as well.

The existence of carbon monoxide in the upper atmosphere of Jupiter is more interesting, since oxygen is not readily available (water, the principal oxygen-bearing molecule, tends to condense in the lower clouds). Several explanations have been proposed. One is that oxygen ions cascade into the upper atmosphere after being injected into the magnetosphere (as SO_2 molecules) by Io's volcanoes. A second explanation is that CO, which forms and remains stable deep in Jupiter's atmosphere, gets transported upward before it can react with hydrogen and thus be destroyed. If this latter scenario is correct, oxygen should likewise react with phosphorus (in the form of phosphine, PH_3) at depth. But phosphine manages to persist in Jupiter's upper atmosphere without being oxidized, which is something of a mystery. Another puzzle is why methane and germane (GeH_4) have been detected but silane (SiH_4) has not. Perhaps all of Jupiter's silicon is tied up with oxygen and resides in the core. A critical unknown is how fast the high-temperature species are convected upward before they are destroyed by chemical reactions.

One insight into vertical mixing comes from the fact that molecular hydrogen (H_2) exists as two species, one in which the spins of the two nuclei are parallel and one in which they are opposed. The two types react and tend to reach an equilibrium ratio that depends on the temperature — as long as vertical motion is weak. However, in a strong updraft, the ratio of the two species “freezes” at the high temperatures found at depth, reflecting conditions at or above 300°K . By observing how the proportions of the two types vary from place to place, atmospheric scientists can gauge how much vertical motion occurs in the equatorial zones of the giant planets. The rate of mixing is greatest for Jupiter and least for Uranus.

The spectacular colors of Jupiter and more muted colors of Saturn provide further evidence of active chemistry in the atmospheres. These colors correlate with the cloud's altitude (Figures 10,11). Bluish regions have the highest apparent temperatures, so they must lie at the deepest levels and are only visible through holes in the upper clouds. Browns are higher up, followed by whites and finally reds. Thus, the Great Red Spot is a very cold feature, judging from its infrared brightness.

The trouble is that all cloud species predicted for equilibrium conditions are white. Therefore, color must arise when chemical equilibrium is disturbed, either by charged particles, energetic photons, lightning, or rapid vertical motion through layers of varying temperature. One possible coloring agent is elemental sulfur, which takes on many hues depending on its molecular structure. Sulfur dominates the appearance of Io, which exhibits many of the same colors as Jupiter. Some scientists believe that phosphine makes the Great Red Spot red, while others have proposed organic (carbon-bearing) compounds to explain almost all of the hues seen in Jupiter's clouds. Since light from solid cloud particles is less diagnostic of their composition than

light from a gas, the coloring agents on Jupiter — and more subtly on Saturn — remain uncertain.

Both the blue-green color of Uranus and the deeper blue of Neptune may have a simple explanation. These planets have so much methane gas in their atmospheres that the gas itself becomes the coloring agent. Methane absorbs red light quite strongly, so the sunlight reflected off the clouds has a blue color.



Figure 14. These views of Jupiter (*top*) and Saturn (*bottom*) were constructed by reprojecting Voyager images as if the spacecraft were looking down onto the planets' south and north poles, respectively. In the Jupiter composite, the Great Red Spot is at upper left; in Saturn's, the dark “starfish” and the two radial “cuts” are processing artifacts. The unusual hexagon centered on Saturn's north pole is actually a six-lobed wave in a zonal jet at 76°N latitude. Seen during Voyager 2's 1981 flyby, it rotated with the same period as Saturn's interior (it did not drift eastward or westward in longitude). Although the origin of the hexagon is uncertain, it may be related to the storm just outside the hexagon in the upper-right quadrant.

Also, these planets' sulfur and ammonia clouds are colder and lie much deeper than those on Jupiter and Saturn, so light reflected from the clouds has to pass through more overlying atmospheric gas on its way to our eyes. The color differences between Uranus and Neptune have to do with the depths of the clouds and the color of the cloud particles themselves.

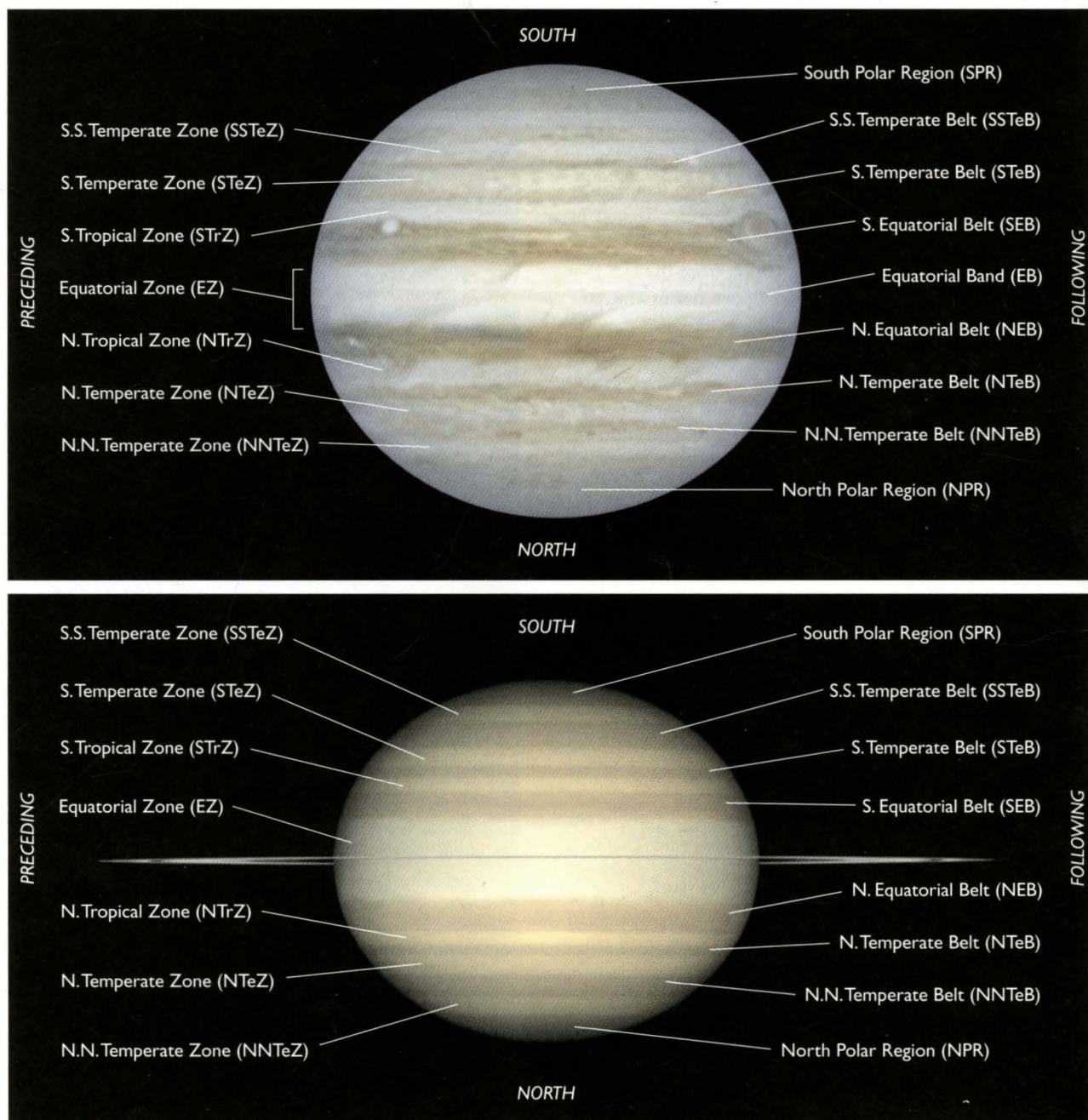
Thus coloration is a subtle process, involving disequilibrium conditions and trace constituents. The correlation with altitude presumably reflects the pressure-temperature conditions need-

ed to drive specific chemical reactions. For example, higher altitudes receive more sunlight and charged particles. Some regions may provide locales for intense lightning and others for intense vertical motion. A different question is why these processes should be organized into large-scale patterns that last for years and sometimes for centuries. This question involves the dynamics of the atmospheres, to which we now turn.

ATMOSPHERIC DYNAMICS

The dominant dynamic features seen in the giant planets' atmospheres are counterflowing eastward and westward winds called *zonal jets* (Figure 7). In this respect, Uranus and Neptune resemble the Earth, which has one westward air current at low latitudes (the trade winds) and one meandering eastward current at mid-latitudes (the jet stream) in each hemisphere.

Figure 15. The names used to designate cloud bands on Jupiter (upper panel) and Saturn have evolved over a century of telescopic observation. These illustrations have south at the top, as they would appear in a backyard (inverting) telescope. Amateur astronomers provide much of the continuity in the historical record of Jovian and Saturnian cloud motions.



Jupiter has five or six of both kinds in each hemisphere, and they are steadier than on Earth. Saturn seems to have fewer sets of such currents than Jupiter, but they move faster. In fact, the eastward wind speed at Saturn's equator is about 500 m per second — about two-thirds the speed of sound there. As on Earth, these winds are measured with respect to the rapidly rotating planets beneath them. Even supersonic wind speeds would be small compared to the equatorial velocity imparted by rotation. (For the Jovian planets, which lack solid surfaces, the rotation rate of their interiors is deduced from that of the magnetic fields generated in their metallic cores; see Chapter 4.)

The zonal winds of Earth are the weakest of any in the solar system, even though the energy available to drive them is greater than on any other planet (Venus is closer to the Sun, but it reflects such a high fraction of the incident sunlight that its absorbed power per unit area is less than Earth's). The total power per unit area (sunlight and internal heat averaged over the surface) at Earth is 20 times that at Jupiter and 400 times that at Neptune. Yet the winds of Neptune are stronger than those of Jupiter, which in turn are stronger than those of Earth. The reason for this seeming paradox may be that, on Earth, sunlight and internal heat create the small-scale turbulence that acts to dissipate the large-scale winds. The turbulence is weaker in the outer solar system, so the winds are stronger. A balloon-borne observer drifting along at 1,000 mph in Neptune's equatorial jet might have a smooth ride.

Without continents and oceans, a planet's rotation tends to produce a pattern of zonal (east-west) currents and banded clouds that remain confined to specific latitudes. One exception is Saturn's polar "hexagon," but this may be merely a wavelike disturbance caused by a storm at that latitude (*Figure 14*). Rotation has two other effects. On Jupiter, Saturn, and Neptune it smears absorbed solar energy into a band around the equator. And on all planets, not just the Jovian ones, it creates the *Coriolis force*, which acts at right angles to the wind.

Uranus provides perhaps the best example of the importance of rotation. During the Voyager encounter in 1986, the Sun was almost directly overhead at Uranus's south pole. The equator was in constant twilight, and the north pole had been in darkness for 20 years (one-fourth of the Uranian "year"). Without the Coriolis force, circulation would have been dictated solely by the need to redistribute heat: winds in the upper atmosphere would blow away from the sunlit south pole and converge on the night side at the north pole, with a return flow underneath. But the Coriolis force is apparently redirecting the flow at right angles to this hypothetical, pole-to-pole circulation, creating the zonal banding seen weakly in Voyager images. Even so, the problem remains that over a Uranian year the planet's poles receive more energy from sunlight than they can emit as infrared radiation. Therefore, to maintain thermal equilibrium the atmosphere *must* transport heat equatorward, via some unseen mechanism that cuts across latitude circles. Small-scale eddies, below the resolution of the Voyager images, are one possibility; transport within the clear atmosphere above the clouds is another.

The infrared instrument on Voyager measured the temperature of the gas above the clouds on each of the four Jovian planets (*Figure 9*). But instead of a smooth gradient from equator to pole, the curves are bumpy, and the latitude zone receiving the

most sunlight is not necessarily the planet's hottest place. A circulation that simply brings heat from warm areas to cold ones would not produce such a distribution. Rather, Voyager investigators believe that heat is being pumped from cold places to hot ones, as in a refrigerator. The power source for this "global refrigerator," they claim, is the kinetic energy of the zonal jets. The steepest gradients of temperature should then be located at the latitudes of the zonal jets (*Figure 7*), and so they are. However, the energy source needed to maintain the jets themselves remains unspecified.

The giant planets' zonal winds are remarkably constant in time. Ninety years of modern telescopic observations reveal no changes in the east-west jets of Jupiter and Saturn. In fact, the basic patterns are so unchanging that astronomers have assigned names to individual latitude bands, calling the dark ones belts and the bright ones zones (*Figure 15*). During the four months

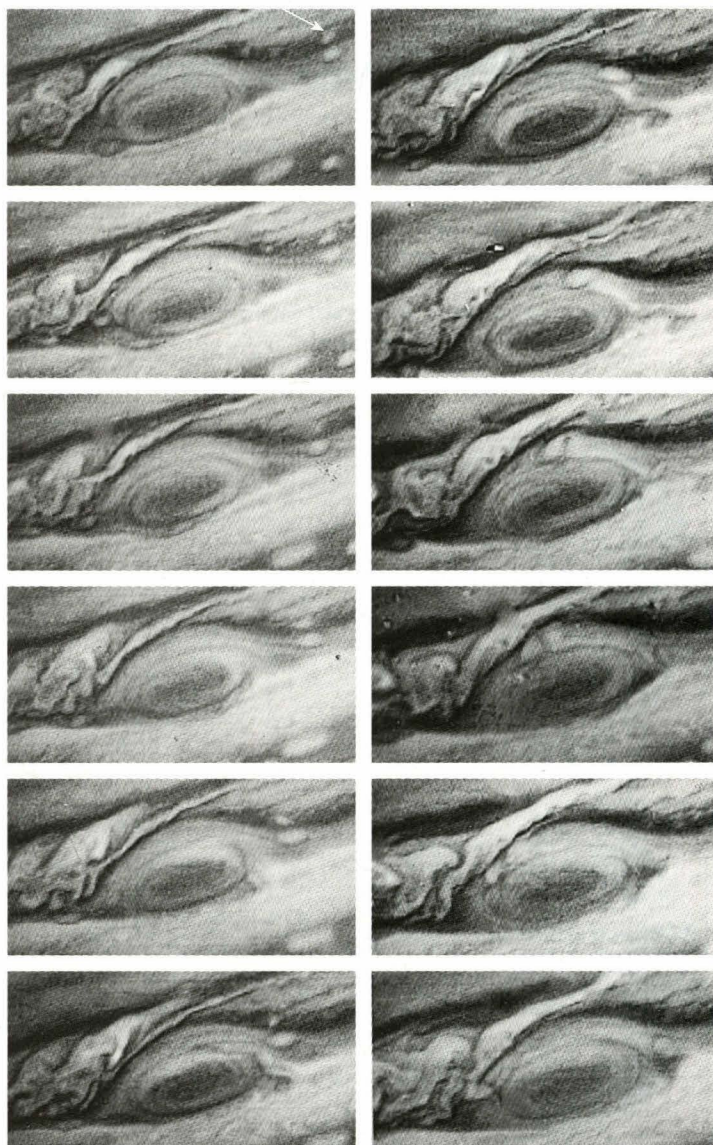


Figure 16. A blue-light image of the Great Red Spot was taken every 20 hours over a period of about two weeks in this Voyager sequence, which begins at upper left, continues down each column, and ends at lower right. Note the small bright clouds that encounter the giant storm from the east, circle counterclockwise around it in 400-km-per-hour winds, and partially merge with it along the southern boundary.



Figure 17. The possible large-scale flow within the giant planets' fluid interiors. Each cylinder has a unique rotation rate, and zonal winds may be the surface manifestation of these rotations. The tendency of fluids in a rotating body to align with the rotational axis was observed by Geoffrey Taylor during laboratory experiments in the 1920s, and was applied to Jupiter and Saturn by Friedrich H. Busse in the 1970s. Such behavior seems reasonable for Jupiter and Saturn if their interiors follow an adiabatic temperature gradient.

between the two Voyager encounters of Jupiter, the planet's zonal velocities changed by less than the measurement error (about 1.5 percent). This is remarkable for several reasons. First, although the zonal jets on Jupiter correlate with the latitudes of the colored bands, the bands often change their appearance dramatically in a few years — while the jets maintain their velocities. Second, as revealed in the superbly detailed Voyager and Galileo photographs, an enormous amount of eddy activity accompanies the zonal jets. Small eddies appear suddenly along the boundary between eastward- and westward-moving streams. They last only about 1 to 2 days, as they are quickly sheared apart by the counterflowing winds. Larger eddies, including a group of long-lived white ovals and the Great Red Spot in Jupiter's southern hemisphere, manage to survive by rolling with the currents. Voyager repeatedly observed smaller spots encounter the Red Spot from the east, circulate around it, then partially merge with it (*Figure 16*). How the zonal jets and the large eddies can exist amid such activity is something of a mystery.

We learned an important fact about the eddy motions from a statistical analysis of Jupiter's winds. During the Voyager flybys, the motions of tens of thousands of 100-km-wide cloud features were tracked. We were intrigued by localized eddies, which moved at about one-fourth the mean speed of the surrounding zone. Their motions were not entirely random. Cloud parcels moving *into* a jet from another latitude were typically headed in the same direction, and thus carried the same eastward or westward momentum as the jet itself. Parcels moving *out of* a jet typically had the opposite sign of momentum (opposed the flow). The net result is that such eddies help to

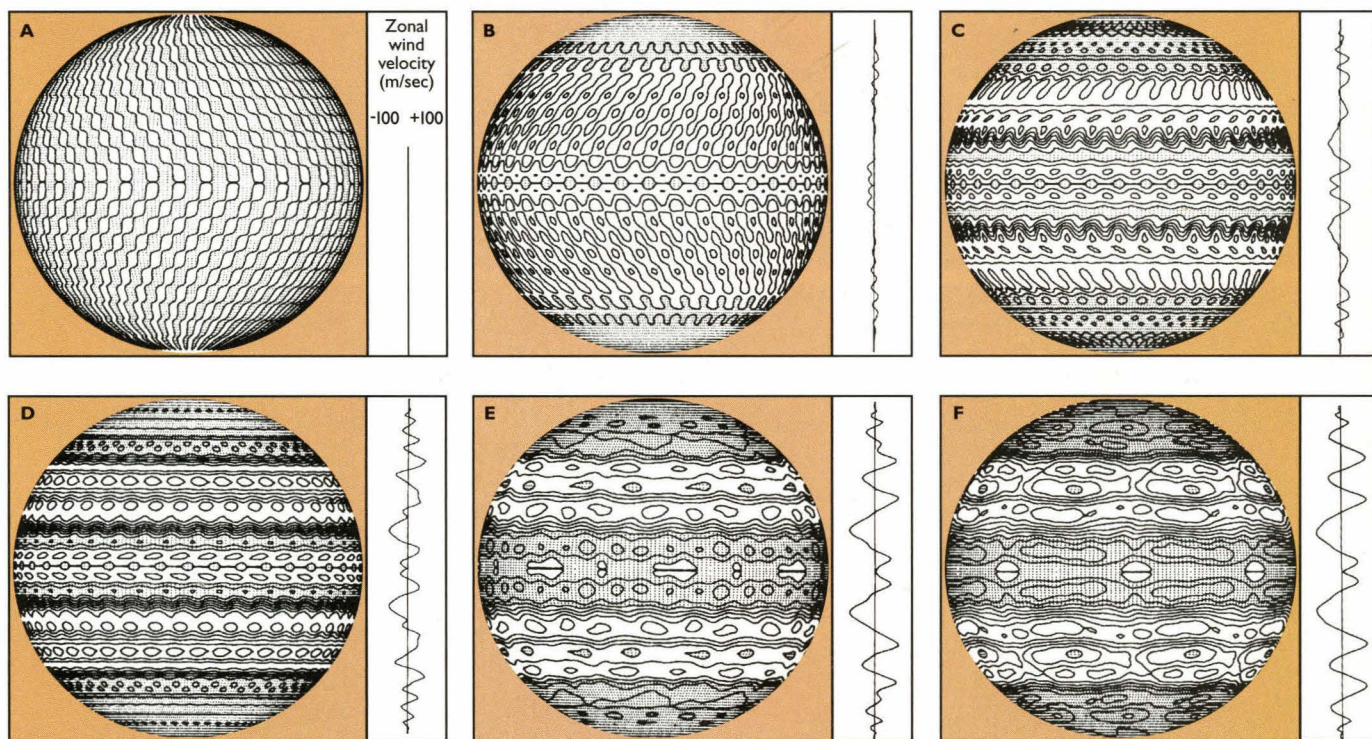


Figure 18. A computer model of Jovian atmospheric circulation made in 1978 by Gareth P. Williams. He assumes that all the activity is taking place in a thin “weather layer” of atmosphere (as is the case on Earth); the fluid interior plays a passive role. This model first produces small-scale eddies (*a*), which become unstable (*b*) and give up their energy to zonal jets (*c,d*) that eventually dominate the flow (*e,f*).

Eddies with deep roots demonstrate the same behavior, so remaining questions center on the depths of both the eddies and the zonal flow. Although the energy source for these motions is uncertain, motions in the weather layer are presumably driven by sunlight, and deeper motions are driven by Jupiter's internal heat.

maintain the jets, not weaken them. Yet no matter how many eddies came and went, the jet speeds did not change. So there must be other, unseen eddies — turbulence on a smaller scale, perhaps — that draw enough of their energy from the jets to keep the system in balance.

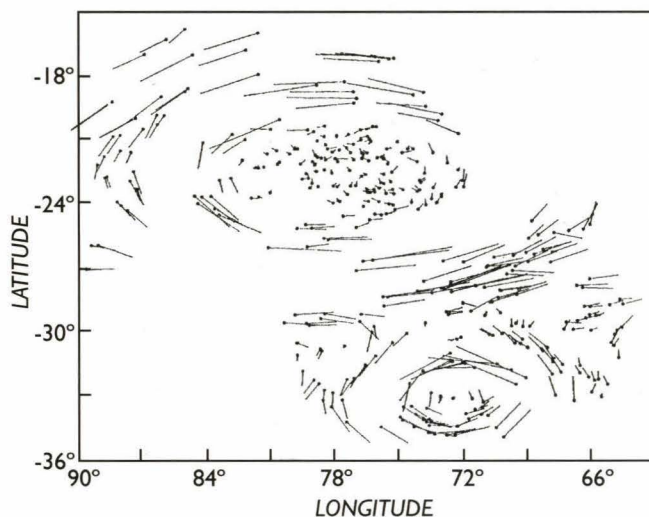
If one regards the zonal jets as an ordered flow and the eddies as chaotic, these observations suggest that (in Jupiter's case) order arises from chaos. Similar interactions among eddies and mean flows occur in the Earth's atmosphere and oceans. In all cases, the eddies get their energy from buoyancy (hot fluids rising and cold ones sinking). Almost all of this buoyant energy is dissipated as heat. On Earth less than 1 percent of it goes into powering the atmosphere's jets, but on Jupiter the fraction exceeds 10 percent. What causes this fundamental difference is unknown, but eddies do appear to drive zonal flows in a wide range of situations on rotating planets. In fact, years before the Voyagers' arrival, atmospheric scientists proposed this mechanism as a way to explain Jupiter's zonal flow (*Figures 17, 18*).

The constancy of Jupiter's zonal jets is remarkable in light of this incessant eddy activity. If all the action were somehow confined to the planet's observable atmosphere, the eddies would be

Figure 19. A wealth of detail appears in a Voyager 1 mosaic (*below*) of the Great Red Spot and a white oval (known as BC since its formation more than 60 years ago). The diagram (*right*) shows wind vectors in this region, determined from changes observed over a 10-hour period. Each dot marks the position of the cloud feature measured; an attached line points in the direction of flow, and its length is proportional to the wind velocity.

doubling the kinetic energy of the jets every 75 days. Obviously, that is not the case. Perhaps the zonal jets have remained stable for nearly 90 years because the mass involved in their motions is many times greater than that of the eddies. That is, if the eddies were confined to cloudy layers, at or above the 5-bar pressure level, the jets would have to extend down to much greater pressures — possibly even through the planet and out the other side!

Such behavior is not as unlikely as it first seems. A rapidly rotating sphere with a fluid, adiabatic interior should exhibit two types of small-amplitude motions (relative to the basic rotation). The first are rapidly varying waves and eddies. The second are steady zonal motions defined by a series of cylinders coaxial to the spin axis (*Figure 17*), with each cylinder turning at a



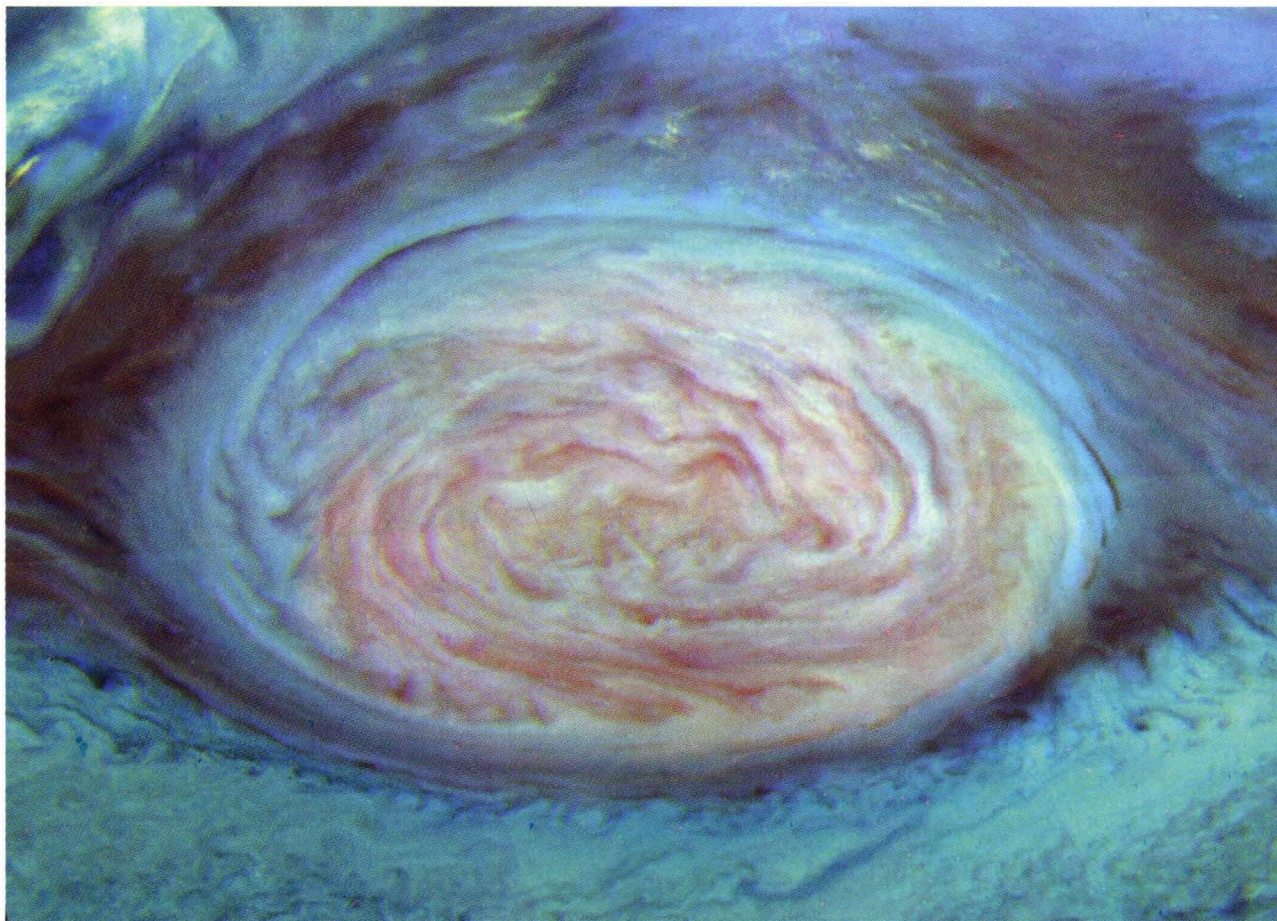


Figure 20. The Galileo orbiter acquired this infrared mosaic of the Great Red Spot in June 1996. It is color-coded so that pink and white indicate the highest clouds (in its center) and blue from the deepest ones (around its periphery) — spanning an altitude range of more than 30 km.

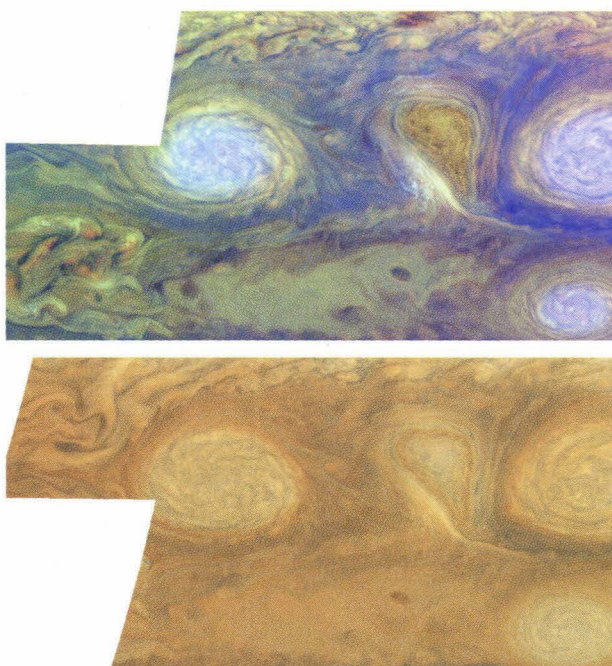


Figure 21. Natural- (*lower panel*) and false-color (infrared) views of Jovian white ovals as seen by the Galileo spacecraft. The larger two ovals, named DE and BC, formed in 1938 and merged into a single oval (BE) in early 1998. Flow around these ovals is counterclockwise, and the pear-shaped region between DE and BC has clockwise flow. Colors in the upper panel indicate that the clouds in the ovals are high while those in the pear-shaped region are low.

unique rate. The observed jets on the giant planets, as far as we know, could be the surface manifestations of an internal clockwork of nested cylinders on a huge scale.

The problem with such speculation is that we lack information about winds far below the visible cloud tops. A totally different approach is to treat Jupiter simply as a larger version of the Earth, whose atmosphere has a fixed lower boundary (our planet's surface). Computer simulations of the Earth's atmosphere have also yielded realistic zonal wind patterns when applied to Jupiter (*Figure 18*). This is somewhat surprising, since the models assume an atmosphere less than 100 km thick and no outward heat flow from the interior.

Clearly, the lack of data on vertical structure within the Jovian planets allows us plenty of “latitude” in trying to explain the zonal jets of both Jupiter and Saturn. Ultimately, we may learn which is correct by comparing the secondary effects predicted by each model with actual observations.

LONG-LIVED STORMS

Theorists have proffered a similarly wide range of theories concerning long-lived oval “storms,” which were well known on Jupiter many decades before being discovered on Saturn and

Neptune by Voyager. Jupiter's legendary Great Red Spot (GRS) covers 10° of latitude (*Figures 19,20*), which makes it about as wide as the Earth. The GRS takes about 7 days to spin around, with winds along its outer edge reaching 400 km per hour. The three white ovals slightly to the GRS's south (named BC, FA, and DE) first appeared in 1938, and spots BC and DE merged in 1998.

These long-lived ovals, which drift in longitude but remain fixed in latitude, tend to roll in the boundary region between opposing zonal jets. The circulation around their edges is almost always counterclockwise in the southern hemisphere and clockwise in the northern hemisphere, indicating that they are high-pressure centers. They often have cusped tips at their east and west ends. During the Voyager encounters in 1979 both the GRS and the white ovals had intensely turbulent regions extending to their west, but when imaged by Galileo in the mid-1990s the white ovals were crowded together with the turbulent regions caught in the middle (*Figure 21*).

Although Saturn is normally rather bland, the Voyagers discovered that it too can display long-lived storms (*Figure 22*). Moreover, the planet occasionally erupts with an outbreak of bright clouds obvious even through backyard telescopes. These disturbances seem to occur every 30 years, which is close to the orbital period of Saturn. The most recent one began in September 1990 as a discrete white spot north of the equator. It quickly spread around the planet and filled the region from the equator to 25° north latitude (*Figure 23*), then faded a few months later. The cause of these periodic eruptions is unknown. They are apparently triggered during summer in Saturn's northern hemisphere — but they have not been observed when summer moves to the southern hemisphere 15 years later.



Figure 22. This oval spot, photographed on two successive Saturn rotations, shows anticyclonic rotation (clockwise in the northern hemisphere) around its periphery. North is to the upper right. The spot's latitude is 42.5° north, and its long axis spans 5,000 km.

Neptune's large oval structures oscillate more and drift farther than Jupiter's ovals. During the Voyager encounter in 1989, Neptune had two major dark features, dubbed the Great Dark Spot (GDS) and Small Dark Spot (*Figures 24,25*). As Voyager 2 watched, the GDS stretched and contracted while rocking and rolling with a period of 8 days (*Figure 26*). Surprisingly, such behavior is consistent with the simplest type of hydrodynamic flow, that of a frictionless fluid (no shearing forces) moving in two dimensions (motion confined to a plane). The success of this simple model lends further support to the idea that small-scale turbulence is nearly absent in the outermost giant planets, since turbulence is three-dimensional and tends to produce shearing forces. Meanwhile, the GDS was also drifting equatorward at 15° per year. At this rate it should have reached the

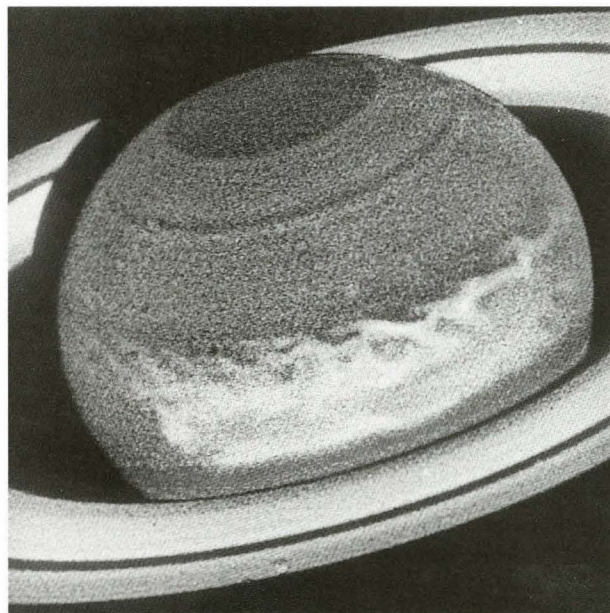


Figure 23. Storms on Saturn, as captured by the Hubble Space Telescope. The disturbed equatorial band in the black-and-white view is the result of an eruption that began on 25 September, 1990. Such major onsets happen about every 30 years, during summer in Saturn's northern hemisphere, but as yet there is no explanation why they appear to follow such a cycle. A smaller storm broke out in September 1994; seen in the color image, it had an east-west extent of some 13,000 km, about one Earth diameter. The bright storm clouds are crystals of ammonia ice that condense in an upwelling of warmer air, similar to a terrestrial thunderhead. Some 200 years ago an equatorial disturbance of this type enabled William Herschel to make the first estimate of Saturn's rotation period.

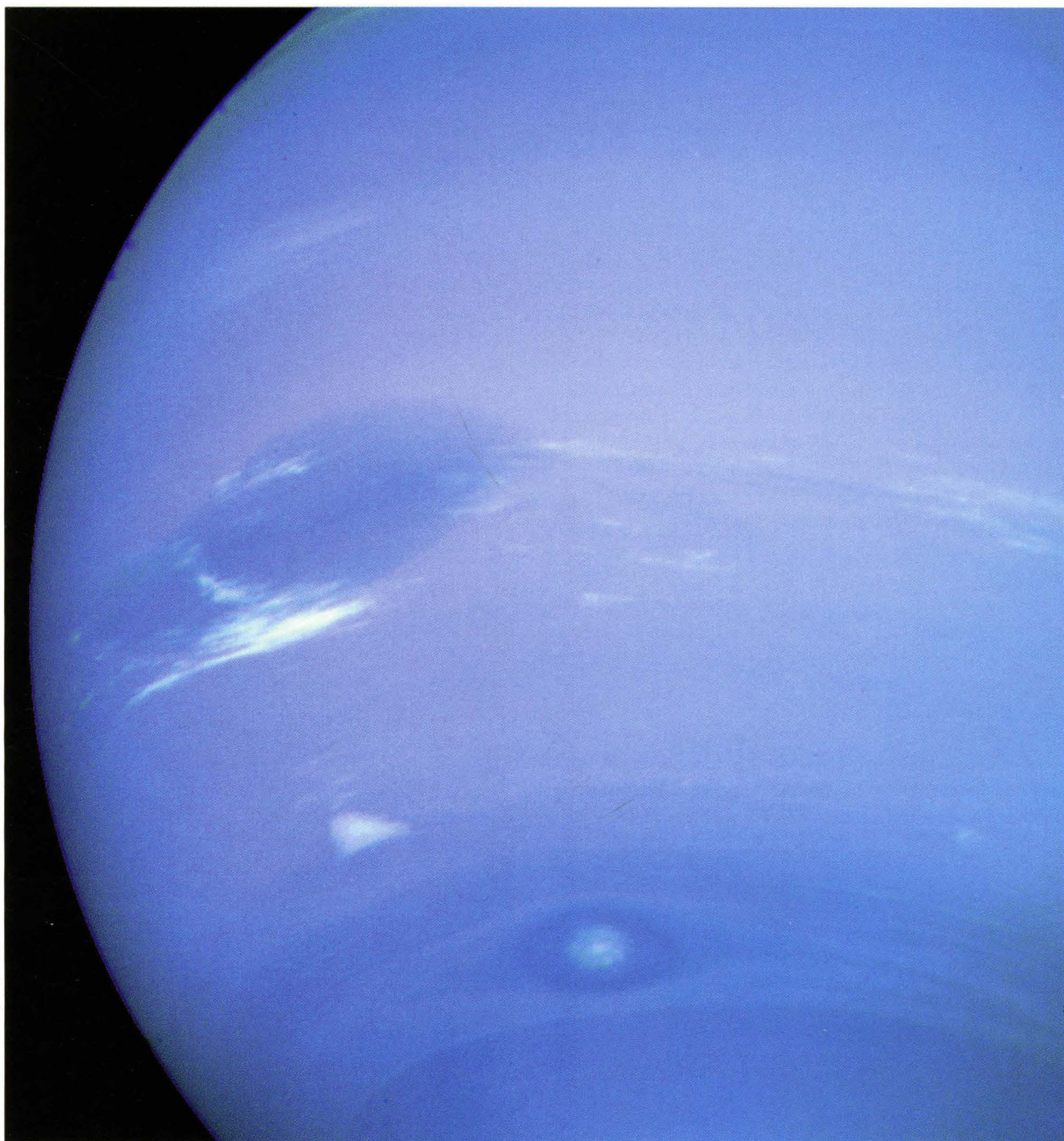


Figure 24. The spots and streamers seen on Neptune by Voyager 2 moved at rates that depended on their latitude. The Great Dark Spot, left of center at latitude 22° south, circled the planet in 18.3 hours. The eyelike Small Dark Spot, near the bottom at 55° south, took only 16.0 hours. The bright cirrus-type patch between them at 42° south latitude was dubbed "Scooter" because its 16.8-hour trips around Neptune were faster than those of other bright clouds. As Voyager watched, Scooter changed shape from round to square to triangular. Neptune's clouds are only barely discernible from Earth.

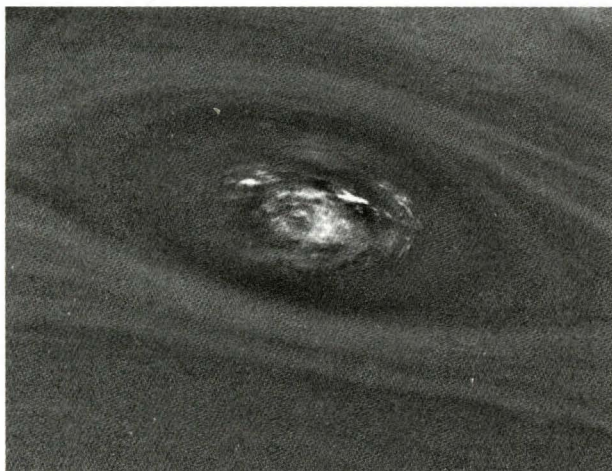


Figure 25 (left). A Voyager closeup of Neptune's Small Dark Spot, also known as D2, shows knots of bright, methane-ice clouds in its center. The spot may have been rotating clockwise, unlike the much larger Great Dark Spot. If so the material within the dark oval was descending.

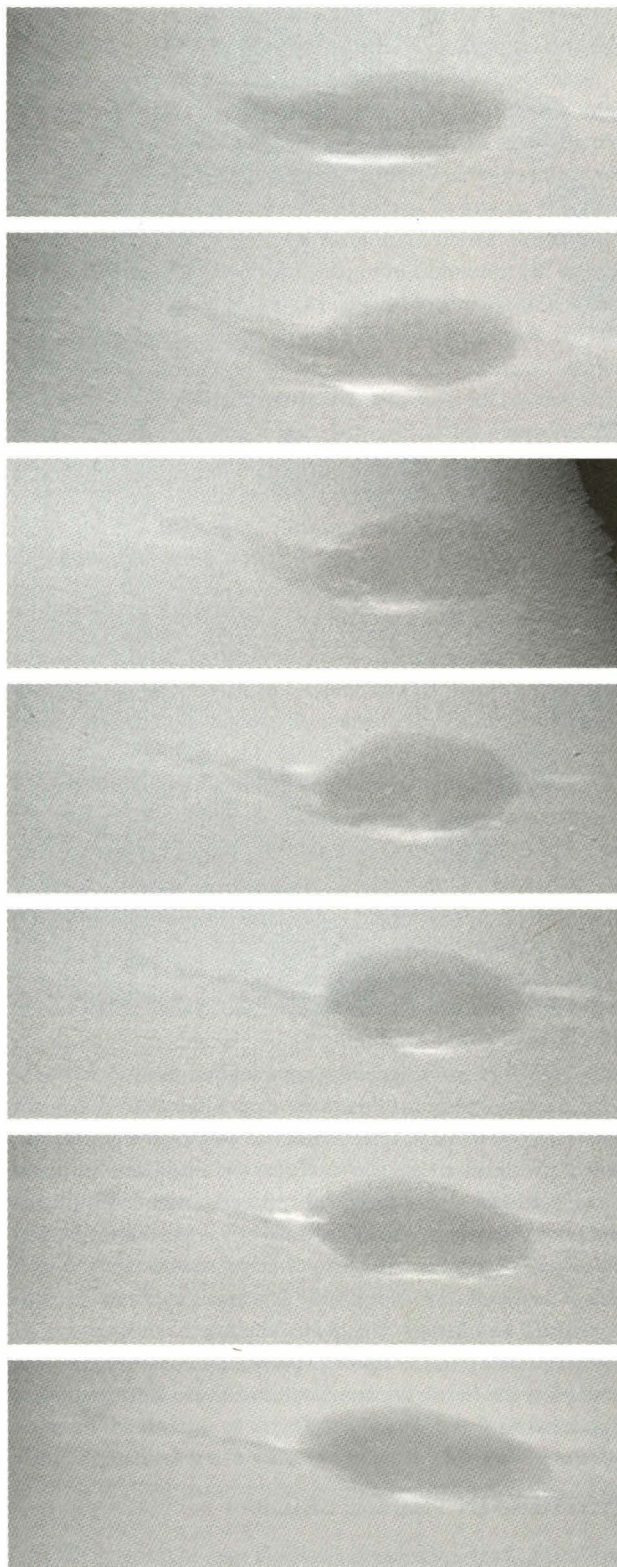


Figure 26. Neptune's Great Dark Spot (GDS), recorded on seven successive rotations of the planet over $4\frac{1}{2}$ days. This sequence shows most of the spot's 8-day oscillation cycle: the GDS is initially elongated toward upper right; then it contracts; and finally it elongates again, this time toward upper left. As noted by Lorenzo Polvani and his colleagues, these features can be reproduced in a simple hydrodynamic model — though modeling the development and collapse of the dark plume at left remains problematic. Note the bright methane-ice clouds along the spot's southern edge, which did not change position over time.

equator (where there is a strong westward jet) a year or two later. More recent observations with the Hubble Space Telescope suggest that it did not survive this passage (*Figure 27*).

Any theory of the GRS, GDS, and other ovals must explain their longevity, which is a twofold problem. The first concern is maintaining the hydrodynamic stability of rotating oval flows. An unstable oval would break up into waves and eddies that would disperse the initial energy over large distances. In that case they would last only a few days, which is roughly the circulation time around their edges (or the lifetime of smaller eddies that are pulled apart by the zonal jets). The second concern is their source of energy. A stable eddy without an energy source to power it will eventually run down, though on Jupiter this could take several years and on Neptune conceivably much longer.

How do theorists account for the long lifetimes of the giant planet's oval storms? The "hurricane" model postulates that these structures are giant convective cells extracting energy from below (the latent heat released when gases condense). The

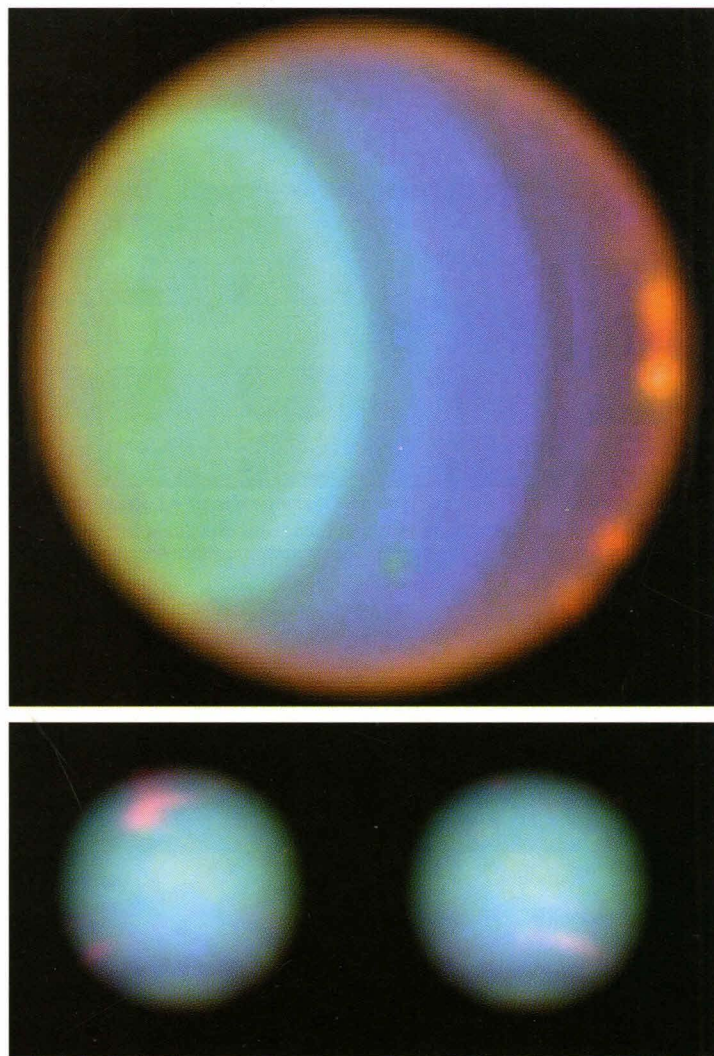


Figure 27. The Hubble Space Telescope turned its gaze to Uranus (*top*) in 1997 and Neptune (*bottom, left and right*) in 1995. The appearance of both planets had changed dramatically since Voyager 2's flybys. Seen in a false-color infrared composite, Uranus displayed a string of bright clouds (along right edge) to the north of its equator — at latitudes completely hidden in darkness when the spacecraft visited in 1986 — and a distinct south-polar "hood." Neptune, meanwhile, showed no trace of its large dark spots.

“shear instability” model holds that they draw energy from the sides (the shear in the zonal currents). Still another model argues that they gain energy much as the zonal jets do: by absorbing smaller, buoyancy-driven eddies. When simulations are run on high-speed computers, the surprising result is that all three hypotheses seem to work. Oval-shaped features form spontaneously in a variety of circumstances that mimic all the likely energy sources, density distributions, and other conditions that have not been completely measured. They roll between the zonal jets just as Jovian vortices do. They grow by merging (*Figure 28*), the largest spot tending to consume all

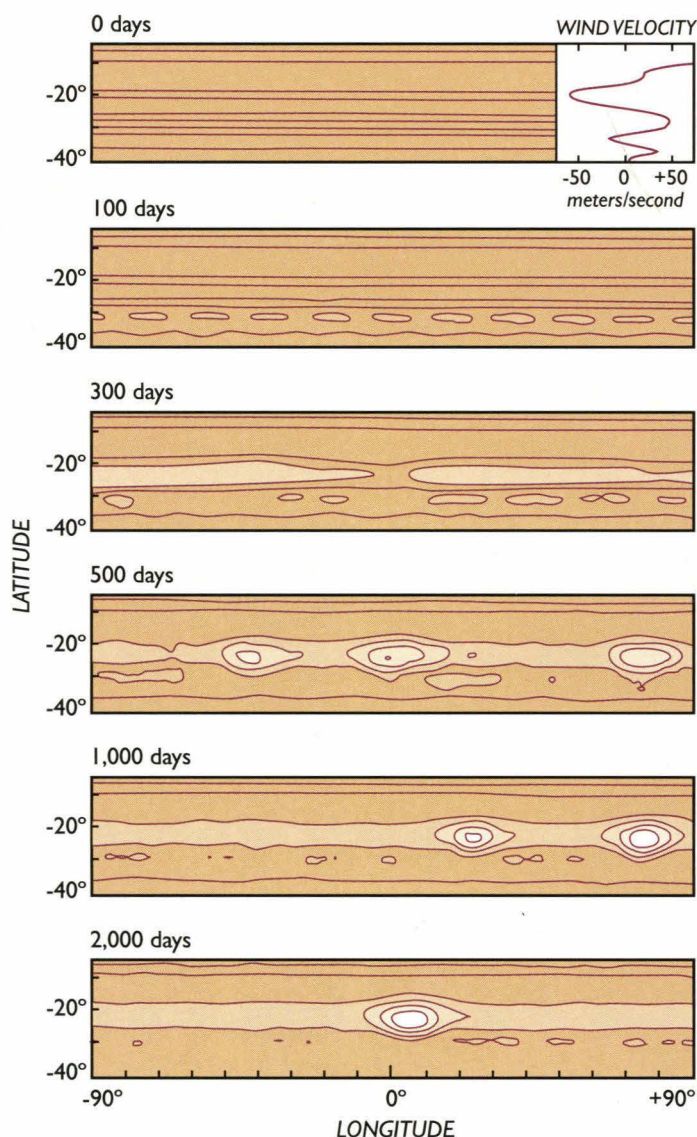


Figure 28. In this computer simulation by Timothy Dowling and the author, Jupiter’s atmosphere is assumed to be a single shallow layer of fluid on a rotating spheroid. Supporting the fluid from below is a much deeper layer, in which different latitudes rotate at different rates (see *Figure 17*). This creates a “washboard” topography at the base of the upper layer. Lines denote contours of constant pressure and thus essentially represent streamlines of the flow. East-west velocity is plotted at upper right. Energy is pumped into the zonal flow, which initially breaks into numerous small eddies because it is unstable. But in time the eddies merge, ultimately yielding a single dominant vortex.

the others in its latitude band. Several groups have observed stable isolated ovals in laboratory simulations of flows (*Figure 29*).

Faced with this unavoidable success, we ponder what the atmospheric models have in common that makes them all work. They all share the equations of fluid mechanics — Newton’s laws applied to atmospheric motion on a rotating planet. Perhaps the growth of a vortex by merging represents the natural outcome in a rotating fluid. As such, the giant-planet atmospheres are the simple examples; the more-complex Earth may lack a Great Red Spot because its continents and oceans tend to disrupt zonal flows, and its large equator-to-pole temperature differences make the atmospheric flows continuously unstable. By contrast, the giant planets’ atmospheres appear to be connected to enormous thermal reservoirs with massive inertia. Temperature differences encountered at a given altitude are therefore smaller, and the flows are steadier — at least on the largest scales. If their interiors really are in differential rotation (*Figure 17*), the inertia of these flows might also contribute to the steadiness of the atmospheres.

But which models best represent a specific planet like Jupiter? Here observations are the key. One sifts through Voyager images to see if vortices come in all size ranges (they do) and whether the small ones behave differently from the large ones (the small ones are rounder). One makes detailed measurements of winds and temperatures, and compares these quantitatively to our computers’ output. Eventually some models will fail to fit the data, and at that point we will have learned something new about Jupiter.

As an example of this ongoing process, consider the mapping of hidden topography using the conservation of angular momentum. When a rotating fluid parcel flows over a topographic rise, its vertical thickness decreases and its horizontal area increases. Like a spinning figure skater throwing out her arms, the fluid parcel reacts by spinning more slowly. A topographic depression produces the opposite effect. On giant planets “topography” arises from the flow below the clouds, which produces an uneven interface at cloud base. Spinning parcels are observed at the cloud-top level, and we assume that the gas in between (the cloudy layer) has been stretched or squashed accordingly. The result of this study is that the layer below the clouds does not act like a flat, solid surface. The GRS appears to be relatively shallow to the north, and it increases steeply in depth to the south (*Figure 30*). The inferred zonal jets below the clouds are comparable to those measured in the upper layers.

MOTIONS IN THE INTERIOR

In closing, let us speculate on possible roles that the giant planets’ fluid interiors may play in their atmospheric dynamics. Consider, for example, whether an interior could help maintain the poles and equator at the same surface temperature, even though the input of sunlight varies with latitude. An adiabatic atmosphere has constant temperature at each altitude level, regardless of latitude, and vertical convection is normally very effective at producing and maintaining such an adiabatic state — especially when the atmosphere’s heat sources are located below its heat sinks. This is the arrangement at least for Jupiter, Saturn, and

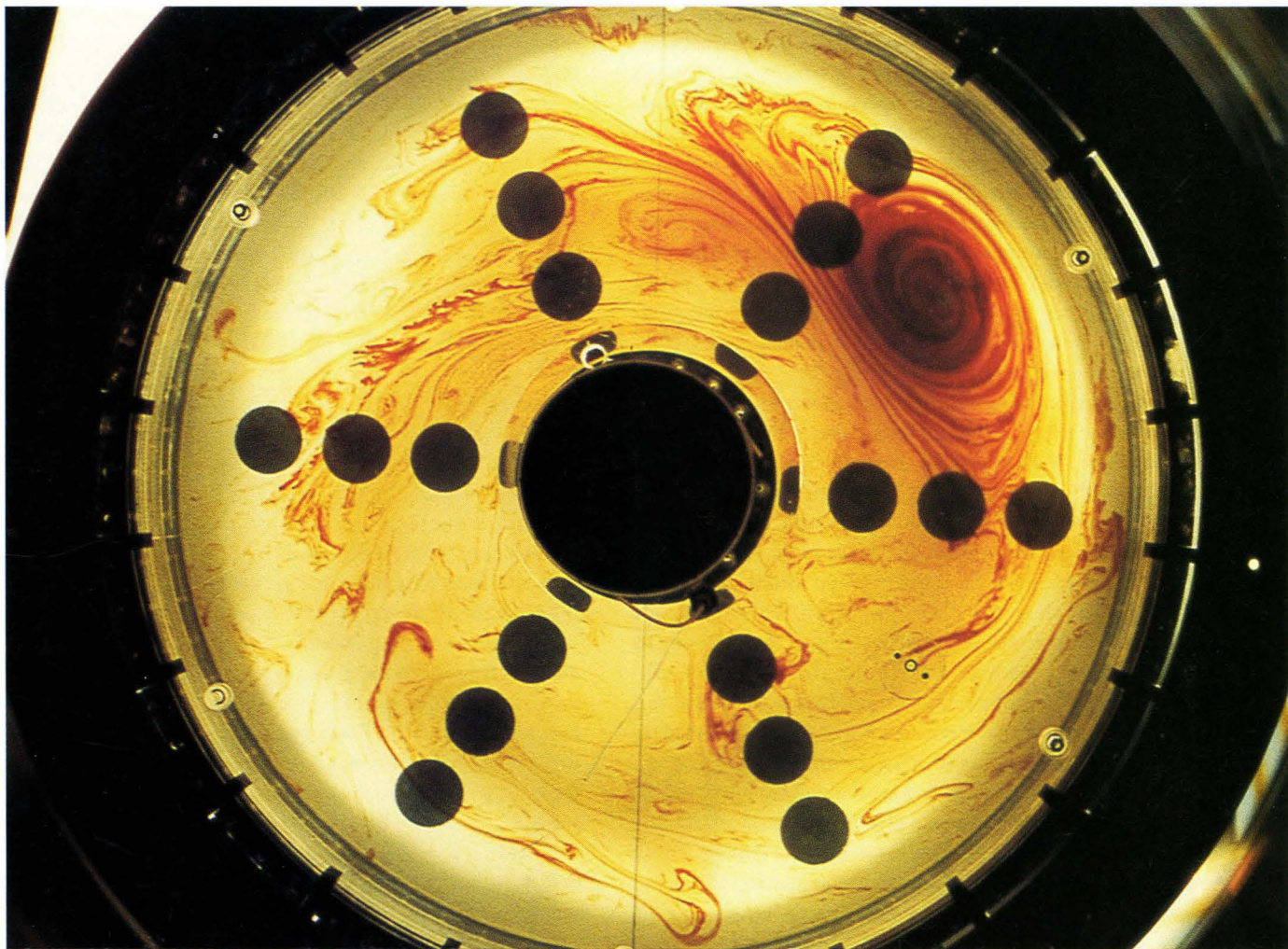


Figure 29. This laboratory simulation shows a spinning cylindrical tank, in which a circular zonal jet has been created by injecting or removing fluid using the 18 circular ports. Over time the zonal jet forms, becomes unstable, and breaks up into small eddies that eventually coalesce into a single, long-lasting vortex. Red dye, injected into the vortex after it formed, is unable to escape.

Neptune, whose interiors generate a great deal of heat and whose atmospheres lose it (via infrared radiation) to space.

Actually, we need to know these atmospheres' *net* heat loss: the infrared energy they emit to space minus the sunlight they absorb. For Jupiter, Saturn, and Neptune, the net heat loss is greatest at the poles and least at the equator; to compensate, heat must somehow be transported poleward. (The reverse is true at Uranus; see *Figure 9*.) But this transfer does not appear to be taking place in the cloud layers — that would disrupt the well-ordered banding. So we expect, but cannot yet know for sure, that small departures from a strictly adiabatic state have arisen in the interior to drive the internal heat flow poleward. These departures are too small to manifest themselves, but the result is that the atmosphere is effectively short-circuited by the interior.

The situation is very different on Earth. Here substantial poleward transport of heat *must* take place in the atmosphere. Absorption of sunlight by the oceans and the subsequent release of latent heat from the condensation of water in the atmosphere above them leads to a net heat gain in the tropics. Radiation to space leads to a net heat loss in the polar atmosphere. This combination sets up appreciable temperature gradients with latitude, and obvious mixing takes place across latitude circles. Consequently, Earth's atmosphere is decidedly *not* adiabatic.

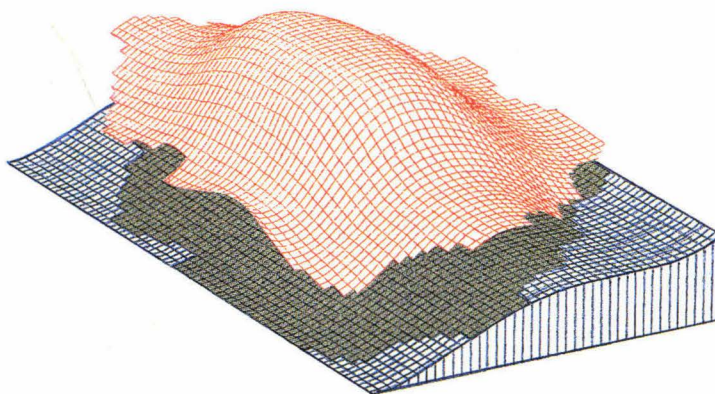


Figure 30. Topography can be inferred for the Great Red Spot (GRS) of Jupiter. This shows the computed shape of two constant-pressure surfaces, the upper one at the cloud tops (0.5 bar) and the lower one at the cloud base (5.0 bars). The lower surface is flat and shallow to the north (right) but slopes down to the south (the vertical scale is greatly exaggerated). The dome in the upper surface indicates that the GRS is a high-pressure center.

Another key speculation is how the Jovian planets' zonal velocities change with depth. According to the thermal wind equation of meteorology, the change of velocity with depth is proportional to the change of temperature with latitude. Since no significant temperature gradients were found on either Jupiter or Saturn by the Pioneer and Voyager instruments at the deepest measurable levels, the velocity change with depth must therefore be extremely small, and so the winds measured at the cloud tops must persist below. A rough estimate is that the eastward wind speeds (relative to the internal rotation rate) persist well below the region that is affected by sunlight, which is mostly absorbed in the clouds. This leaves internal heat as the obvious source for deep motions.

The Galileo probe provided our only direct measurement of winds below the tops of Jupiter's clouds. The winds were inferred from the Doppler shift of the probe's radio signal as it descended. The probe entered at 6.5° north latitude, where the cloud top wind is eastward at 100 m per second (*Figures 7, 11*). To almost everyone's surprise, the winds *increased* with depth to 180 m per second at the 5-bar level and then held steady to 20 bars, where the probe died. Since this is below the clouds and below the level that is heated by sunlight, it is tempting to conclude that the winds are driven by internal heat. Yet we cannot be sure. The probe results do imply that the winds run deep: they are qualitatively consistent with inferences based on the figure-skater effect (*Figure 30*) and with the idea of differentially rotating cylinders extending throughout the interior (*Figure 17*). But these models do not identify the energy source that maintains the winds. If they are just coasting without friction, the winds might not need a large energy source to continue in their present state essentially forever.

A complete theory of these deep motions is still a long way off. The problem is similar to modeling the motions in the Sun's interior, but the computational challenges are greater. The giant planets are cold objects that radiate their energy slowly, so their interiors take a long time to reach thermal equilibrium. Yet certain atmospheric phenomena (turbulent waves and eddies, for example) change very rapidly. Even the largest computers cannot simulate both the slow, large-scale processes and the fast, small-scale ones simultaneously. To cope at all, meteorologists must use approximations for the fast processes that convey their net effect on the slow ones. Developing such models, even for the well-observed Earth, is something of a black art.

Consequently, despite our great progress in understanding the atmospheres of the giant planets, many fundamental questions remain unanswered: What energy source maintains the zonal winds? Do the winds and the long-lived ovals really have deep roots, or are they confined to the cloud zone? What accounts for the planet-to-planet differences in the zonal wind patterns, and why do the winds increase as one moves away from the Sun? What accounts for the colors of the clouds? Is Jupiter really dry, or did the Galileo probe just hit a dry spot?

The most interesting questions revolve around the profound differences between the giant planets and Earth. We speculate that the cause of these differences may lie in the fluid interiors beyond our reach. But our speculations may turn out to be wrong — the entire circulation may be taking place in the giant planets' thin outer atmospheres. Further analysis of existing data and more theoretical work should resolve many of the questions. But the best answers will come from more capable telescopes dedicated to the giant planets, more orbiting spacecraft, and multiple probes that penetrate deeper than ever before.